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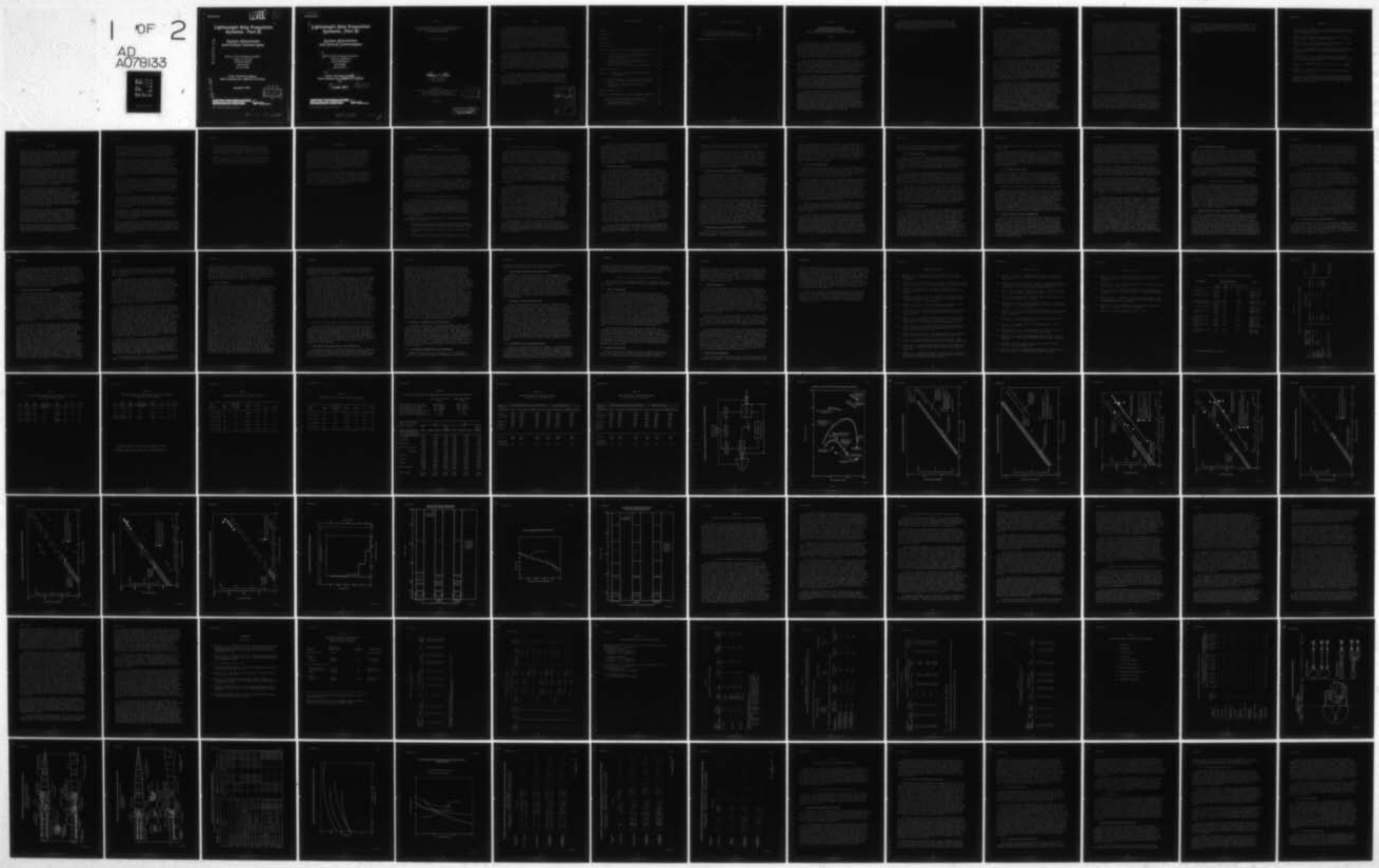

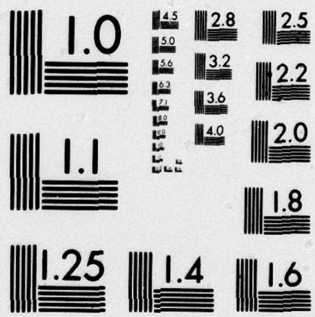
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Lightweight Ship Propulsion Systems - Part III

System Alternatives and Critical Technologies

Simion C. Kuo, Principal Investigator
Travis L. O. Horton
Charles W. Deane
Ho-Tien Shu
Earl R. Fisher

Final Technical Report
ONR Contract No. N00014-77-C-0735

October 1979

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Lightweight Propulsion Systems for Advanced Naval Ship Applications -- Part III - System Alternatives and Critical Technologies

Final Technical Report

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Prepared For:
The Office of Naval Research, Arlington, Virginia
Under Contract No. N00014-77-C-0735
Mr. M. Keith Ellingsworth, Program Monitor

October 1979

FOREWORD

The work described in this Final Technical report was performed at the United Technologies Research Center (UTRC) under Contract N00014-77-C-0735 entitled Lightweight Propulsion Systems for Advanced Naval Ship Applications - Parts II and III. This report summarizes results obtained for the Part III System Alternatives and Critical Technologies study program. Dr. Simion C. Kuo was the Principal Investigator for this contract, and those who assisted in performing this work were: Dr. C. W. Deane (Phase III-1, Electrical transmission Characteristics and Impact); Dr. H. T. Shu (Phase III-2, Comparative Evaluation of Propulsion System Configurations); and Mr. T. L. O. Horton (Phase III-3, Identification of Critical Components Technologies). Mr. E. R. Fisher provided expert assistance in preparing alternative propulsion engine integration and layout schematics.

Because of a decision by the Office of Naval Research in June 1978 to re-emphasize the fundamental research, a subsequent cutback in contract funding from $561,756 to $340,000 was experienced. Accordingly, the original Part III Feasibility Assessment study was revised to reflect a reduced level of effort, and thereby bring the overall lightweight propulsion system study program to an orderly and meaningful conclusion. The revised Part III System Alternatives and Critical Technologies study program which included the first three of the original six phases of study identified in the UTRC Proposal (P77-1) was approved by ONR for completion by the original contract termination date of November 14, 1979.

The contract program was initiated with ONR on August 15, 1977, and the Annual Technical Report for the Part II study was submitted to ONR November 1978. The Program Manager was Mr. M. Keith Ellingsworth, Power Program, ONR, Arlington, Virginia. Valuable guidance and comments received from Mr. Ellingsworth and Mr. John R. Satkowski, Director of Power Program at ONR are gratefully acknowledged.

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Lightweight Propulsion Systems for Advanced Naval Ship Applications Part III - System Alternatives and Critical Technologies

ABSTRACT

SUMMARY

This report presents the technical characteristics of alternative closed-cycle gas turbine propulsion systems incorporating various electrical and mechanical transmissions, and reviews the critical technologies and development requirements for these propulsion systems as part of a comprehensive study program which assesses the technological and economic feasibility of utilizing open- and closed-cycle gas turbines to provide lightweight propulsion power for future Navy capital ship applications. The level of technology considered is that judged by the Contractor to be available for use during the 1990's.

ABSTRACT

The progress made in developing electrical transmissions for naval propulsion applications has been reviewed, and estimates have been made of the performance, size, and weight characteristics of selected electrical transmissions, including Segmented Magnet (SEGMAG) and superconducting generators and motors. The potential influence of these electrical transmissions on the overall propulsion systems performance, weight and layout characteristics as well as on the ship payload and design requirements has been identified.

Alternative propulsion system configurations which integrate the 80,000-shp closed-cycle gas turbine designed previously by UTRC with different types of mechanical and electrical transmissions and thrustors were identified and characterized. A comparative evaluation of the relative technical merits of these alternative propulsion system configurations was made based on a set of evaluation criteria established, and the propulsion systems most suitable for the high-speed and conventional destroyers applications were selected.

Technological predictions reported in the Part I and Part II Technical Reports for the open- and closed-cycle gas turbine propulsion systems were updated during the Part-III study. The crucial components and specific key technologies which require development beyond the level represented by the present state of the art were identified, and various means which could remove these technological barriers and constraints in order to demonstrate a practical lightweight closed-cycle gas turbine propulsion systems for Naval ship applications were analyzed. Major test programs, milestones, and cost schedules identified with the development of the reference closed-cycle gas turbine propulsion systems investigated are also presented.

The Part-III System Alternatives and Critical Technologies study program was conducted by the Energy Conversion Systems Analysis group at UTRC under Contract N00014-76-C-0735 according to a revised, reduced-effort study program approved by the Power Program Branch of the Office of Naval Research, Arlington, Virginia.

INTRODUCTION

There are two major drawbacks to employing compact, high-power-density gas turbine power conversion systems for Naval ship propulsion applications when mechanical transmissions are used. The first drawback is the inherent mismatch between the high-speed turbine output shaft and the low-speed thrustor, a problem which requires high-reduction-ratio gearboxes and very long shafts. The results of the Part-I study (Ref. 1) indicate that the total weight for the gearbox plus shafts is two to four times greater than the weight of the power conversion system itself. The electrical transmission (superconducting or segmented-magnet type), on the other hand, can offer not only variable speed reduction and flexibility of operation but also significantly reduced transmission size and weight. The second drawback is the precise alignment required for mechanical drive which leads to placement of turbines deep in the displacement ship hulls, necessitating large-volume long intakes and uptakes. In high-speed ships, long and complex gear trains reduce not only the ship performance but also the propulsion system reliability.

The advantages of electrical transmissions for naval propulsion application have been well recognized for many years. However, the development of conventional electrical transmissions for ship propulsion applications has been hampered by the large size and weight of these transmissions in the horsepower ranges required for modern naval ships. Many studies (for example, see Ref. 2) have concluded that size, weight, and cost can be reduced significantly if superconducting or SEGMAG (Segmented Magnet) rotating machinery were used. Although the facts that there have been no practical electrical transmissions of these types built for naval ship applications and that many critical technical problems remain to be resolved, substantial progress has been made in the past several years (Refs. 3, 4, and 5).

In the mid-1960's, the Army and Navy sponsored research on rotating superconducting machinery for their own potential applications, and a few, small-killowatt motors have actually been constructed as part of those early projects. In the early 1970's an intense R&D program was initiated at the Naval Ship Research and Development Center, Annapolis branch to build a 400-hp d-c homopolar motor and a 300-kW d-c homopolar generator and to study designs and concepts for more advanced, higher-powered, propulsion systems. The Navy has also supported large programs at Garrett AiResearch and General Electric to design advanced systems, both d-c and d-c/a-c hybrid systems for machinery in the 20,000 and 40,000 horsepower ranges. In the same time period, the Office of Naval Research (ONR) sponsored Massachusetts Institute of Technology and Westinghouse Electric Co. in performing conceptual design and feasibility studies of superconducting and SEGMAG machinery. United Technologies Research Center has been participating in the area of magnetic materials and rotating machinery research activities in the MIT studies (Refs. 6 and 7).

In an effort to assess the technical and economic feasibility of lightweight propulsion systems incorporating closed-cycle gas turbines for advanced Naval ship applications, a comprehensive three-part study was initiated at UTRC in 1976 under the sponsorship of ONR. Previous reports relating to work on this program have presented the results of Part-I Systems Studies (Ref. 1) and Part-II Conceptual Design and Reliability (Ref. 8) of lightweight closed-cycle gas turbine ship propulsion systems. However, these previous studies considered only mechanical transmission systems and excluded those incorporating electrical transmissions; farther, this earlier work did not identify the specific development time and costs required to develop and implement closed-cycle gas turbines for future Naval ship propulsion applications. Assessment of new propulsion concepts by Navy planners should include both of these factors. Therefore, it was planned to devote a significant portion of the Part-III study program to estimating the impact of electrical transmissions on the attractiveness of closed-cycle gas turbine propulsion systems when installed in both high-speed and conventional destroyers.

In order to establish the future capabilities of electrical transmission systems, an extensive review should be made of data in existing reports and the available literature. Additionally, personal discussions should be held with experts in the superconducting and SEGMAG machinery field to ensure the credibility of the projected performance, size, weight, and cost data for electrical transmission systems. These data can be used in estimating the total weight of propulsion systems utilizing the reference design 80,000-shp, closed-cycle gas turbine integrated with different electrical transmissions (superconducting and SEGMAG), so comparisons could be made with the results for systems with mechanical transmissions. A preliminary comparative evaluation, based on a set of criteria selected, should be made to identify the relative technical merits of alternative propulsion configurations. Finally, the critical component design and operational problems for the closed-cycle gas turbine systems should be reviewed, and the possibility of removing or alleviating the critical problems or barriers through technological development, further testing programs, or use of substitute components should be evaluated. Based on the results of these assessments, schedules and cost estimates for specific research and development program which could lead to a demonstration of a reference lighweight ship propulsion system investigated can be outlined.

The results of the reduced-effort, Part-III - System Alternatives and Critical Technologies study program are presented in the three sections of this report. The characteristics of future superconducting and SEGMAG electrical transmission systems estimated are presented in PhaseIII-1. In Phase III-2, many alternative propulsion systems which incorporate several electrical transmission systems and ship layout configurations are compared with the previously designed reference propulsion system (Ref. 8) which incorporates a mechanical transmission. Phase III-3 discusses the critical component technologies for

the closed-cycle gas turbine systems in terms of the state-of-the-art, extension of applicable technologies, and technological barriers and constraints. The possibilities of removing these barriers and constraints and the required test and development schedules and costs estimated are also presented in this phase of the report.

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CONCLUSIONS

1. Among the various naval ship types evaluated, a conceptual high-speed destroyer in the 35(to 4000 tons displacement range would benefit the most from implementing the lightweight closed-cycle gas turbine propulsion systems, offering a 50/20 knots max/cruise speed capability and approximately 100-hour endurance (duty) with 10 percent or more payload. Advanced open-cycle gas turbines might offer the only alternative propulsion power for the same destroyer, but with lower payload or shorter endurance or both.

2. Using two 80,000-shp conceptual-design closed-cycle gas turbines each driving one high-rpm supercavitating propeller for the high-speed destroyer mentioned above, an epicyclic gear transmission (two needed) was rated to offer the highest overall technical merit (179 out of possible 200) closely followed by a SEGMAG electrical transmission system (176/200). The former transmission system would provide a propulsion system specific weight of 11.4 lb/shp and the ship payload would be approximately 20 percent (displacement) for the 150-hr cruise or 10 percent for the 100-hr duty cycle operation.

3. If closed-cycle gas turbines are considered for the conventional destroyer (35/20 knots) propulsion applications, an 80,000-shp reference engine coupled with two SEGMAG genertors to power two SEGMAG motors, each driving a fixed-pitch propeller, would offer the highest technical merit (176/200) compared with other systems using mechanical (157/200) or superconducting electrical (160/200 for AC and 166/200 for DC) transmission systems. However, the previous Part I study concluded that closed-cycle gas turbines offer no significant advantages over open-cycle gas turbines for conventional destroyer applications, unless a nuclear heat source is used.

4. Ten evaluation criteria, each carrying a selected weighing factor (between one and five), were judged as significant in rating the technical merits for twelve alternative propulsion configurations. These criteria are: lightweight (5), compactness (5), fuel efficiency (5), reliability/maintainability (5); ship layout (4), auxiliary requirements (4), control and response (4); operational flexibility (3), projected capital cost (3); and development requirement (2).

5. Despite the near-constant thermal efficiencies at part-load due to use of inventory control (of working fluid) for power variation, a closed-cycle gas turbine propulsion system can still save a substantial amount of fuel if an electrical transmission is used instead of

mechanical transmission. In the case of the high-speed destroyer mentioned earlier, the potential fuel saving would be at least 4 percent for duty cycle operation and 16 percent or more for cruise. Potential fuel savings attributable to use of electrical transmissions will be significantly greater for open-cycle gas turbine propulsion systems because of its poor partload performance with mechanical drives.

6. When compared with the superconducting (S/C) transmission systems, SEGMAG transmissions offer the inherent advantages of being less complex in construction, requiring no liquid-helium cryogenic subsystems, and being free from potential failures attributable to the accidental loss of superconductivity. However, the SEGMAG transmission would be slightly heavier than the S/C transmissions, weighing between 2.24 and 3.70 lb/shp (compared with 2.20 and 3.40 lb/shp for S/C system) for thrustor speeds of 580 and 230 rpm, respectively, considered for the high-speed and conventional destroyers.

7. The use of an advanced electrical transmission (SEGMAG or S/C) would offer not only the potentially attractive fuel savings indicated above, but also greater flexibility/versatility in Naval ship layout and operation, and reduced ship size without compromising the mission capabilities. However, weight savings for the shorter transmission shafts will not be significant (approximately 0.7 and 0.2 lb/shp, respectively for the conventional and high-speed destroyers) because the heavy-duty outboard shaft can not be reduced in length.

8. At a given torque rating, the weight and volume of either SEGMAG or superconducting DC machines would be approximately one-quarter the weight and volume of conventional electrical equipment. The projected unit capacity limits for these advanced electrical transmissions would be able to meet the power ratings required by the conventional and high-speed destroyers considered.

9. Implementation of lightweight closed-cycle gas turbine propulsion systems for high-speed Naval ship applications would require development of main-shaft thrust bearings and high-speed thrustors (such as the super-cavitating propeller) capable of operating at power levels beyond those of current-technology systems.

10. A further understanding of helium flow dynamics and heat transfer characteristics, particularly in the area related to turbomachinery aerodynamics and heat exchanger/ducting pressure losses, represents one of the most critical research effort in developing viable closed-cycle gas turbine power systems, because these characteristics provide a basis for improved design of all the power system components.

11. Development of reliable ceramic materials for use in heaters of closed-cycle gas turbines would significantly improve the attractiveness of these propulsion engines for Naval ship applications. These ceramic materials must exhibit sufficient impact strength and corrosion resistance in a low-quality fuel combustion environment.

12. Development of a closed-cycle helium turbine propulsion system will require approximately seven to ten years and would cost over $340 millions. Based on current observations, the helium heater and the turbomachine will be the two most costly components to develop.

RECOMMENDATIONS

Although closed-cycle gas turbines offer the potential of lightweight propulsion systems for improving mission capabilities of advanced Navy capital ships, it would appear unlikely that this type of marine propulsion engine will be built and installed aboard a ship before 1990. The open-cycle gas turbines, on the other hand, are already operating on land, in the air, and aboard ships, and have demonstrated great promise for future Naval propulsion applications. However, at least two major problems in open-cycle gas turbines, namely, controllability/maneuverability and reduction in specific fuel consumption (SFC) remain to be improved, such as through use of electrical transmissions.

In this context, it would appear logical that the vast technological information and consistent systems evaluation methodologies developed during the current study program be extended directly to evaluate the technical merits of open-cycle gas turbines integrated with advanced electrical transmissions for conventional as well as conceptual high-speed destroyer applications. This recommended study should represent a timely effort which would produce meaningful results at a modest cost.

PHASE III-1

ELECTRICAL TRANSMISSION CHARACTERISTICS AND IMPACT

In the previous phases of this study program, the transmission type considered for integration in the closed-cycle helium turbine for lightweight ship propulsion application was limited to the mechanical-type gear drive. These mechanical transmissions were found to contribute significantly to the total propulsion system weight as well as fuel weight requirements because of their bulkiness and operational limitations at part power. Electrical transmissions, particularly SEGMAG (Segmented Magnet) versions, might overcome some of these problems. Therefore, in the first phase of this Part III study program, characteristics of potential electric transmission systems were projected and their possible impact on propulsion system performance, weight, and layout characteristics was identified.

The results of Phase III-1 reported here include: (1) summary of the technological status of rotating electrical machines; (2) descriptions of weight, size and performance characteristics of electric transmissions; (3) estimates of the weights and sizes of total propulsion systems with either electrical or mechanical transmissions; (4) discussions of advantages and disadvantages of mechanical and electrical transmissions; and (5) estimates of the impact of electrical transmissions on ship design.

1.1 Technical Status of Rotating Electrical Machines

Electrical transmissions for marine propulsion applications offer the potential of high availability and reliability, but the excessive weight and size characteristics of conventional electrical rotating machines (generators and motors) have precluded the use of electrical transmissions in past naval ship applications. Alternatively, SEGMAG and superconducting electrical rotating machines are expected to be substantially lighter and smaller than conventional machines and may therefore be competitive with or even superior to mechanical transmissions.

In general, electrical transmissions have the following major advantages over mechanical transmissions:

1. The power generation and drive equipment may be mechanically separated, thereby improving the part-load fuel economy and reducing shaft length.

2. The power plant arrangement and location within the vessel are more flexible.

3. Control flexibility with variable speed reduction ratio is increased.

4. Full power is available for rapid reverse operation.

With an electrical transmission, the output speed, and therefore, the "effective" gear ratio can be varied electrically over a wide range. This wide variation means that a prime mover (such as a gas turbine) can be operated at its most efficient shaft speed for a given power level, and that a fixed-pitch propeller can be used without a reversing gearbox or turbine. In direct gear transmissions driven by gas turbines, a controllable, reversible-pitch propeller is often used to provide reversing capabilities and low-speed maneuverability.

A schematic diagram of a superconducting electrical transmission which would join the prime mover (gas turbine) to the thrustor is shown in Fig. 1.1. Excitation equipment is used to control the power and speed of the generator and the motor, while the cryogenic refrigeration system provides liquid helium at 4.2 degrees Kelvin to maintain superconductivity. (A dynamic braking resistance which is required to absorb power during motor reversal is not shown in this schematic diagram.) The schematic diagram of a SEGMAG electrical transmission is the same, except that no cryogenic refrigeration system would be required.

The phenomenon of superconductivity was discovered by Onnes in 1911, but early superconducting materials had such low critical field intensity and current density limits that these materials had little application in practical devices. It was not until the early 1960's that practical superconducting alloys (such as niobium-tin and niobium-zirconium) with high critical field and current limits were developed; further, these alloys are sufficiently ductile that they can be fabricated in many shapes and wire sizes. With the availability of practical superconductivity materials, the list of potential applications was expanded to include rotating electrical machines. In 1964, Stekly and Woodson (Ref. 1.1) assessed the performance improvements believed possible with the increased current densities and field strengths of superconductors when compared with conventional materials. Their study, which examined AC alternators for central power plants, reported that three-phase alternators at ratings of 1000 kW and greater would be an order of magnitude lighter than conventional machines at the same rating. Further, for these large machines, the power requirement necessary to produce superconducting temperatures would be only 0.1 percent of the machine rating.

In 1966, Frankel, et al. (Ref. 1.2) conducted the first analysis of superconducting machines for marine propulsion. Since that time, conceptual designs of superconducting motors and generators have been prepared for several marine applications. Although most of the work sponsored by the US Navy has been concerned with DC machinery, some efforts have also been directed toward the use of AC machinery.

In general, DC electrical machines are desirable for marine applications because these machines provide continuous and rapid control of the ship's thrustors, thereby providing good maneuverability and high efficiency. Superconductors were first applied to DC machines of the homopolar configuration. However, the homopolar configuration requires that the electricity be transmitted to the rotor at a high current and a low voltage; this combination produces a problem with current collection in machines with high power ratings. Because of this problem, machines with high power ratings have traditionally been of the AC type in which the electrical terminals are directly connected to stationary armature windings.

1.1.1 Superconducting AC Machines

The greatest amount of development work on superconducting rotating electrical equipment has been directed toward AC generators, because these devices are expected to reach early commercial application in central power plants. In 1969, Thullen (Ref. 1.3) designed and tested an 87-kWe machine that had a superconducting field winding which rotated at 3600 rpm inside an insulating vessel. Based on this experimental work, Thullen prepared a conceptual design of a 1000-MWe (at 3600 rpm) superconducting turboalternator. Subsequently, Appleton (Ref. 1.4) presented a conceptual design of a 500-MWe superconducting AC generator, while Parker and Towne (Ref. 1.5) summarized a Westinghouse conceptual design of a 1200-MWe unit. Glebov, et al. (Ref. 1.6), in a review of Russian work on large superconducting AC turbogenerators noted that a 200-kWe superconducting AC generator was tested in 1975, a 20-MWe generator prototype of large generators has been designed and is being constructed, and a conceptual design of a 2000-MWe AC generator with superconducting field windings was prepared.

The first systems design study of superconducting machinery for marine propulsion was completed in 1970 by Greene (Ref. 1.7). This design was for a 28-knot two-shaft Coast Guard ship with 13.5 MW (18,000 shp) per shaft at an output speed of 229 rpm. Each shaft had one generator rated at 13.5 MW at 3600 rpm. On the basis of DC-brush-current technology existing at that time, Greene selected superconducting AC synchronous generators and motors. To vary the speed of the synchronous motor, a cycloconverter was chosen over a rectifier/inverter; the cycloconverter is a device which varies the amount and frequency of its output power. An advantage of the cycloconverter is that during shaft reversal when energy is absorbed by the propeller, power can flow in either direction through this device without restricting the power factor.

The other major study where superconducting AC machinery was preferred for marine propulsion was sponsored by the Office of Naval Research (ONR). The work, completed by Westinghouse in the first year of a three-year program, was published in 1977 by Thompson, et al. (Ref. 1.8). This work was directed

Concurrent to this General Electric work, AiResearch (Ref. 1.16) also conducted a design feasibility study of DC superconductive propulsion equipment.

More recently, Appleton, et al. (Ref. 1.17) constructed and tested a laboratory model of a superconducting electrical transmission. A 1-MWe superconducting DC (homopolar) generator is driven at constant speed by a diesel engine; electric power from the generator is transmitted to a superconducting DC homopolar motor which, in turn, is connected to a water brake. The Ward-Leonard principle is used to control the system, with DC generator output controlled by varying the current in its superconducting field winding; power from the generator is sent to the superconducting motor at a voltage which can be varied continuously from zero to maximum.

1.1.3 Advanced Non-Superconducting SEGMAG Machines

Recent work at Westinghouse (Ref. 1.18) sponsored by the Navy indicates that segmented magnet (SEGMAG) electrical generators and motors are very competitive with superconducting DC equipment on the basis of weight and size. In the SEGMAG concept, cooling is accomplished with deionized water, and metal graphite brushes are used to collect the current. At each operating condition, the required speed and torque of the propulsion motor are produced by a different generator voltage and current obtained by varying the generator field. The fields of the motors and generators are controlled by separate exciters. Feedback during the dynamic operation of the machines is sent to the exciter controls and also to the supervisory controller. The latter also receives manual input from the control console. Signals from the supervisory controller initiate startup and shutdown, and change the power level as required.

Though the SEGMAG machines are in an early stage of development, they are very attractive because their weight characteristics are similar to those of superconducting machines, but without requiring the complication of a cryogenic subsystem. Three factors result in SEGMAG machines being lightweight as compared to conventional electrical generators and motors. First, the conductors inside the actual machine are cooled with deionized water so that current levels are higher than in conventional machines. Second, the latest current collection techniques are used. Third, the air-gap magnetic flux density is somewhat higher than in conventional machines. The principal features of SEGMAG machines include a circumferentially segmented magnetic circuit, an armature winding mounted on the surface of the rotor iron, direct cooling of the electrical conductors with deionized water, and solid graphite brushes operating at very high current densities.

1.1.4 Capacity Limits of Rotating Electrical Machines

Data presented in Fig. 1.2 show capacity limits of rotating electrical machines as a function of machine speed as well as the design points of selected designs and hardware. These data were collected from a number of sources and

toward a high-performance ship (such as a hydrofoil or surface effects ship) with 18.6 MW (25,000 shp) per thruster shaft. This study found that when superconducting AC motors are compared with conventional DC motors, the former would be lighter than the latter, but would have approximately the same specific weight as superconducting DC motors being developed by other investigators. Various speed control devices were reviewed in the study, but no decision was made concerning the best approach. In Ref. 1.9, McCann and Mole summarized earlier Westinghouse work on the design of a superconducting AC generator (5 MWe at 3600 rpm) for marine propulsion.

1.1.2 Superconducting DC Machines

Superconducting DC homopolar machines have been chosen by the Navy for development because they best meet ship propulsion requirements. These machines can supply full torque at all speeds; have relatively low refrigeration requirements because the magnet does not experience torque; and offer a directly varying speed reduction ratio between the generator and motor.

A number of studies have considered the use of DC superconducting machinery. The Navy through NSRDC has done extensive development on superconducting DC (homopolar) motors (Ref. 1.10) and generators (Ref. 1.11). Because good superconducting materials have relatively low mechanical strengths, the rotors in these designs are placed inside the magnetic field to minimize rotor stresses. The ferromagnetic iron shield used to confine the magnetic flux represents two-thirds of the machine weight. Based on this work, Stewart (Ref. 1.12) performed a systems analysis of electric transmissions with DC machinery. This design incorporated two shafts, each of which incorporated two generators and one motor; each generator was rated at 14.9 MW at 3300 rpm, and the homopolar motor was rated at 29.8 MW (40,000 shp) at 180 rpm.

In 1977, Stevens, et al. (Ref. 1.13) summarized the NSRDC development work with superconducting machines and presented designs based on this work for superconducting DC motors for 29.8 MW (40,000 shp) at 180 rpm. These advanced designs require liquid cooling of the rotating armature and liquid metal current collectors.

In addition to these systems studies of electrical machinery for marine propulsion, other work on superconducting DC motors and superconducting generators has been summarized by various other investigators. Appleton (Ref. 1.14) presented estimated weights and sizes of superconducting DC motors for marine application; metal-plated carbon fiber brushes were used for current collection. In this application, the motor speed is controlled by the armature voltage through generator field control; the generator is driven at constant speed under all operational conditions. In another study, GE (Ref. 1.15) built a 2.2 MW (3000 shp) DC superconducting motor (at 1000 rpm) for testing by the Navy. In this unit, liquid-metal brushes are utilized for current collection.

are discussed in the following section. Because there are no superconducting rotating electrical machines that can be purchased "off the shelf" at this time, all superconducting machines are one-of-a-kind special designs.

1.1.4.1 AC Machinery Limits

In Fig. 1.2, the projected ratings for superconducting AC generators were obtained from Glebov (Ref. 1.6) and from Bratoljic (Ref. 1.19), while the ratings of conventional AC generators were obtained from manufacturers' catalogs. The ratings of AC generators, both those which are currently available and those which are for projected superconducting designs, are well above the 60 MW size that is presently envisioned for high-performance marine propulsion systems.

No superconducting AC (synchronous) motors have been built, but there have been conceptual designs of 18.6 MW (25,000 shp) units (c.f., Ref. 1.8), and conventional AC motors are available (Ref. 1-20) on special order at the 74.6 MW (100,000 shp) level (e.g., for use on LNG tankers). Conventional AC motors are more highly developed than are conventional DC motors since with the former there is no problem of transferring electric power across the moving contacts.

The limit shown in Fig. 1.2 for conventional AC motors is essentially techno-economic based on an estimate by Baltisberger, et al. (Ref. 1.21); this limit is approximately an order of magnitude larger than currently available hardware. No capacity limit projection for superconducting AC motors was found in the literature, but the upper limit is expected to be higher than that for conventional AC motors, because i^2R losses are generally much lower in superconducting motors. Hence, if AC motors (either conventional or superconducting) were to be selected for marine propulsion, capacity limits are anticipated to be well above the 60-MW size currently envisioned for marine propulsion.

1.1.4.2 DC Machinery Limits

In DC machines, there is no way of avoiding the transfer of current from a moving to a stationary contact, and therefore current collection methods are critical. Appleton (Ref. 1.22) estimated the capacity limits shown in Fig. 1.2. With superconducting machines, design values of the magneto-motive force can be much larger than in conventional machines since higher magnetic fields can be generated in the gap without creating resistance losses (i^2R) in the superconducting windings. To date, the ratings of the DC superconducting hardware that has been built are well below those projected by Appleton. Even conceptual superconducting designs have ratings well below these projections, although this is due in part to the lack of demand for this equipment. Because most previous marine design studies showed a need for approximately 18.6 to 29.8 MW (25,000 to 40,000 shp) per shaft, this was the size at which motors and generators were designed. However, recently, Stevens et al. (Ref. 1.13) indicate that the Navy technology base is being developed to use superconducting

electric transmission systems in the range of 29.8 to 55.9 MW (40,000 to 75,000 shp) per shaft.

The largest superconducting DC motor (Ref. 1.22) that has been built to date is a 2.4 MW (3250 shp) unit that operates at 200 rpm. However, there are conceptual designs of superconducting DC motors with ratings to 29.8 MW (40,000 shp) (e.g., Ref. 1.13). A large conventional DC motor rated at 4.5 MW (6000 shp) and 130 rpm was built on special order by Westinghouse (Ref. 1.20) for use on the U.S. Coast Guard ice breaker, Polar Star, but there has been only a small commercial demand for these large motors. In this design, a Ward-Leonard type of control was used.

1.1.4.3 SEGMAG Machinery Limits

Also shown in Fig. 1.2 are the design points for the nonsuperconducting SEGMAG motor and generator. This type of electrical equipment is very competitive on the basis of weight, size, and efficiency with superconducting designs. Because SEGMAG machines are in an early stage of development, capacity limits have not been identified yet, but it is believed (Ref. 1.18) that machines can be built with a capacity of at least 29.8 MW (40,000 shp).

1.2 Weight, Size and Performance Characteristics of Electric Transmissions

Based on the data summarized in Section 1.1, the weight, size and performance characteristics were estimated for SEGMAG and both AC and DC superconducting generators and motors. Presently, there are no off-the-shelf superconducting motors or generators, and of the few pieces of prototype hardware that have been built, none is as large as the designs with ratings envisioned in previous marine studies. Whereas the weight, size, and performance characteristics of conventional motors were obtained directly from manufacturer's catalogs. It became apparent that the conceptually designed SEGMAG and superconducting equipment generally weigh about one-quarter as much as does the conventional equipment. The only nonsuperconducting machines whose weights are comparable to superconducting equipment are SEGMAG motors and generators (Ref. 1.18).

1.2.1 Weight and Volume of Electric Transmissions

Figures 1.3 and 1.4 present the weight and volume characteristics of DC generators as a function of the full-load torque factor (shp/rpm), and Figs. 1.5 and 1.6 present the weight and volume characteristics of DC motors as a function of the same torque factor. The weight and volume of the DC SEGMAG machines are similar to those of the superconducting machines, and as noted, both SEGMAG and superconducting machines generally are substantially lighter and smaller than the conventional machines. The experimental superconducting homopolar generators and motors being investigated by the Navy and shown in Figs. 1.3 and 1.5 are probably heavier than necessary and hence, likely weigh more than would a ship-board version.

Based on the estimates of machinery weight and size, linear regression lines were faired through the available conventional machinery data. In each case, a second line was drawn parallel to the weight and volume data for conventional equipment and used to represent the superconducting equipment because the data available for superconducting equipment seem to indicate a relationship with approximately the same slope (within its scatter). However, the limited volumetric data for superconducting DC motors have a lower slope, and the working line was placed accordingly. In this manner, the assumed weight and volume characteristics shown in Figs. 1.3 to 1.6 could be used for the superconducting DC generators and motors discussed in Section 1.3.

Figures 1.7 and 1.8 present the weight and volume characteristics of AC synchronous generators. The characteristics of the air-cooled propulsion generators are based on data by Harrington (Ref. 1.23), whereas the majority of the estimates for superconducting AC synchronous generators is based on conceptual designs for large central power plants in the 500 MWe to 1000 MWe class.

Figures 1.9 and 1.10 show the weight and volume characteristics of AC synchronous motors. The special-order propulsion motor points (shown as darkened squares) are based on data from Ref. 1.23. Very little effort has been directed toward developing superconducting AC motors because a suitable application has yet to be identified, and as discussed, the Navy is more interested in developing DC motors for marine propulsion. The superconducting motor designs in Fig. 1.9 having full-load torque factors in the range of .075 to .75 kW/rpm (0.1 to 1.0 shp/rpm) were prepared for an aviation application (Ref. 1.24).

In addition to the generators and motors required for an electrical transmission, other components are also required. Greene (Ref. 1.7) estimated the following weights of the auxiliary equipment required for his 13.4 MW (18,000 shp) superconducting AC electrical transmission system: the helium liquefier was estimated to weigh about 1905 kg (4200 lbm), or .14 kg/kW (0.2 lbm/shp); the braking resistor, transmission bus, and cycloconvewrter would weight about 1590 kg (3500 lbm); or 0.12 kg/kW (0.2 lbm/shp). In another case, Stewart (Ref. 1.12) estimated the weight of the auxiliary equipment required for his superconducting DC electrical transmission system. At a design point rating of 59.7 MW (80,000 shp), the estimated weight of the helium compressor and cryostat was approximately 4536 kg (10,000 lbm), or .08 kg/kW (0.13 lbm/shp); the weight of the transmission lines, switchgear, and rheostats (to match voltages when bringing generators on and off line, when switching in crossover, and when reversing the motors) was estimated to be approximately 97.1 kg (17,000 lbm), or .128 kg/kW (0.21 lbm/shp). In a further case for a 59.7 MW (80,000 shp) SEGMAG system (Ref. 1.8) the weight of the required auxiliary equipment (exciters, controls, transmission lines, switchgear, braking system, and lube oil system) totaled approximately 18,144 kg (40,000 lbm), or .30 kg/kW (0.5 lbm/shp).

1.2.2 Electric Transmission Performance

Table 1.1 presents estimates of the full-load efficiency of superconducting equipment. Most of the values cited are estimates, because the MIT-EPRI generator (Ref. 1.25) is the only machine cited in the table that has been tested. Part-load estimates were not given; based on the data shown in Table 1.2, the part-load efficiency is probably very close to the full-load value. Nevertheless, superconducting DC motors are estimated to provide efficiencies approaching 98 percent, while superconducting generators should show efficiencies of approximately 98.5 percent.

Table 1.2 shows efficiency data on nonsuperconducting equipment. The efficiencies of the SEGMAG equipment are estimates; the efficiency values on the AC synchronous motor are Westinghouse data cited in Mark's Mechanical Engineering Handbook (Ref. 1.26). It should be noted that the efficiency values decrease only slightly from the full-load value as the load is reduced.

1.3 Weight of the Total Propulsion System

Based on the information presented in Section 1.2, the weights and sizes of electrical generators and motors for electric transmissions in CCGT systems can be estimated and can be combined with the weights of the other components of the system to produce estimates of weights for the total propulsion system. Similarly, the weights of the comparable mechanical transmissions can be determined and then combined with the weights for other related system components based on earlier work done on this program (Refs. 1.27 and 1.28). Finally, by combining the transmission characteristics with thrustor characteristics and the specific fuel consumption (sfc) of the CCGT, a calculation can be made for the amount of fuel needed for a given mission, and hence the payload can be estimated. The estimates of propulsion system weights and of payloads are presented in the following subsections.

1.3.1 Weights and Sizes of Selected Electrical Machines

As will be discussed, electric motors which can be used on future naval ships, such as conventional destroyers and high-speed destroyers, depend not only on shaft speed but also on the type and number of propellers specified. The first two columns of Table 1.3 show the selected combinations of power (shp) and speed (rpm) for the electric motors considered. It can be seen that the combinations of speed and power are within the limits shown earlier in Fig. 1.2. DC superconducting machines have been selected since they can supply full torque at all speeds, can operate over a wide range of speeds (as opposed to AC synchronous motors), and have relatively low refrigeration requirements because the magnet does not experience torque. The weights and sizes of superconducting DC motors and generators are very similar to the projected sizes and weights of

superconducting AC motors and generators based on the limited data available; this similarity can be seen by comparing the information presented in Figs. 1.3 to 1.10. Based on two studies (Refs. 1.7 and 1.8), it appears that AC superconducting equipment could weigh perhaps 20 percent less than DC superconducting motors; but the advantages of DC equipment appear to be more important than the lighter weight of AC equipment (Refs. 1.13 and 1.29). Hence the weight penalty associated with selecting the more desirable DC equipment does not appear to be large. Accordingly, at the full-load value of the torque factor, the weight and volume characteristics of electrical machines which are presented in Figs. 1.3 to 1.10 can be used to estimate the weight and volume of other motors under consideration.

1.3.1.1 Weights and Sizes of Superconducting DC Machines

The estimated weights and volumes of superconducting DC motors at the selected full-load conditions shown in the fourth and fifth columns of Table 1.3 were derived from Figs. 1.5 and 1.6. The average length-to-diameter ratio (ℓ/D) values of the eight available designs of superconducting DC motors ranged between 0.75 and 2.0, with six of eight designs having an ℓ/d between 1.5 and 2.0. Since the average ℓ/d value for these superconducting DC motors is 1.6, this ratio was used to calculate the length and diameter of the selected motor from the volume characteristics presented in Fig. 1.6.

A similar approach to estimating the weight and volume of superconducting DC generators used full-load power (shp) and speed (rpm) from Table 1.4 and the full-load torque factor in Figs. 1.3 and 1.4 as critical parameters. The ℓ/d ratio of the three available designs of superconducting DC generators ranged from 1 to 1.3, with an average of 1.2. This average value of the ℓ/d ratio was then used to calculate the length and diameter of each generator, and these results are presented in columns six and seven of Table 1.4 According to the information on capacity limits in Fig. 1.2, the maximum shaft speed of a superconducting DC generator with a design output of 20 to 30 MW is approximately 3600 rpm; however, the maximum shaft speed of a superconducting DC generator with a rating of 59.7 MW (80,000 shp) is about 3200 rpm; hence, the shaft speed of the 59.7 MW generator in Table 1.4 is reduced to 3000 rpm to avoid the capacity limits. This reduction in generator design speed results in a generator that is 3629 kg (8000 lbm) heavier.

1.3.1.2 Weights and Sizes of SEGMAG DC Machines

The estimated weights and volumes of segmented magnet (SEGMAG) electrical motors are shown in Table 1.5; these results were obtained from Figs. 1.5 and 1.6 by placing a line through the one available SEGMAG motor point and with the same slope as the line for superconducting DC motors. The ℓ/d for this one motor design (Ref. 1.18) is 0.7, which is the value used to estimate the length and diameter of the SEGMAG motors in Table 1.5.

Table 1.6 presents estimated weights and volumes of SEGMAG generators at selected operating conditions. Again the results were obtained by placing a line parallel to the line for superconducting DC generators and through the one available SEGMAG generator point in Figs. 1.3 and 1.4. The ℓ/d ratio for this one generator design is 2.2; the value was used to estimate the length and diameter of the SEGMAG generators shown. In the event that the rpm limitation discussed for superconducting DC generators also applies to SEGMAG generators, then the shaft speed of the 59.7 MW design would have to be reduced to approximately 3000 rpm and this reduction results in a generator whose weight is 3175 kg (7000 lbm) more than that of the higher speed machine.

1.3.2 Propulsion System Weight Estimates

Table 1.7 presents a comparison of total weights of CCGT propulsion systems with a mechanical transmission to propulsion systems with electrical transmissions incorporating superconducting DC machinery or SEGMAG machinery. These comparisons are made for a conventional destroyer at 59.7 MW (80,000 shp) and also for a high-speed destroyer at 119.4 kW (160,000 shp). The conventional destroyer has the 59.7 MW (80,000 shp) CCGT system; the high-speed destroyer with a mechanical transmission is estimated to be 2/3 the weight of the power conversion system. This is consistent with the method used in Ref. 1.27, because the weight of the bedplate in a DD 963 is approximately 60 percent of the power conversion system weight. Based on information in Ref. 1.18, the weight of the bed plate in the system with a SEGMAG electrical transmission is approximately 2/3 of the weight of the bed plate of a similar system incorporating a mechanical tranmission. This factor of 2/3 was assumed valid for all systems incorporating electrical transmissions with either SEGMAG or superconducting DC machinery.

The weight of the mechanical transmission was determined using methods reported in the Phase-I report of this program, assuming current technology, and adding 30 percent to allow for the gearbox support. Current technology was assumed, because this is the basis on which the electrical machinery characteristics were reported. Presumably, further technical advances will allow lighter-weight designs to be made for both superconducting DC and SEGMAG machines, but it is difficult to project such advances because both types of machines are new. Hence, current technology was assumed as the common ground for estimating the characteristics of both mechanical and electrical transmissions. A K-factor of 200 (Ref. 1.27) was assumed for the non-reversible gearbox installed in the conventional destroyer; for the epicyclic reversing gearbox in a high-speed destroyer, the K-factor was assumed to be 250 (which is conservative because gearboxes being built for marine applications have already achieved a K-factor of 280). The weight of the electrical transmissions was derived from the information presented in Section 1.3.1. Based on information in Section 1.2.1, an auxiliary equipment allowance of .30 kg/kW (0.5 lbm/shp) was added to the weight of the motors and the generators. Further, .06 kg/kW (0.1 lbm/shp) was added to the weight of the electrical equipment for the small

epicyclic gearbox that is located between the gas turbine and the generator, because the maximum generator speed is approximately 3600 rpm at the power levels of interest (See Fig. 1.2) and the gas turbine operates at a design speed of 4800 rpm.

Estimates of the weight of the shafting were based on the length of the shafting obtained from the layout drawings prepared in Phase III-2. In making these estimates, the inboard length was segregated from the outboard length, because the outboard section is generally the heavier (per unit length) of the two sections. For the weight of the inboard shafting on the high-speed destroyer, the line of weight per length shown in Fig. D-4 of the Phase I report on this program (Ref. 1.27) was used, at a shear stress level of 843 kg/cm^2 (12,000 psi) at the design point, and a diameter ratio (z) of 0.65. The weight per unit length of the outboard shafting was taken as 33 percent higher, since that is the relationship indicated by the data for actual shafts in Fig. D-4 of Ref. 1.27. For the shafting on the conventional destroyer, the same procedure was used except that the allowable shear stress at the design point was reduced to 703 kg/cm^2 (10,000 psi).

The weight of the thrustor was estimated from the information presented in Fig. 1.11 of the Phase-I report of this program (Ref. I.27). For a conventional destroyer, requiring a 17-ft diameter thrustor, a titanium CRP thrustor used with a mechanical non-reversing transmission has a specific weight of .94 kg/kW (1.54 lbm/shp, while a titanium FP thrustor used with an electrical transmission has a specific weight of .49 kg/kW (0.8 lbm/shp). For a high-speed destroyer a 3.1 m diameter cavitating FP thrustor is required, and when produced from titanium, the total subsystem weight is estimated at .09 kg/kW (0.14 lbm/shp). This latter specific weight estimate is for a propeller yet to be developed, and therefore, it may be conservatively high. Next, the combined weight of the miscellaneous components (such as control equipment, fuel and oil treatment systems, pumps, generators, etc.) was estimated to be 30 percent of the subtotal weight, and this is tabulated in the "Others" category in Table 1.7. Finally, the weights of the heater system which also include the weight of the support structure and of the intake and the uptake are taken directly from the Phase-II report of this program (Ref. 1.28).

The last line of Table 1.7 shows the estimated total weight of the propulsion systems. For the conventional destroyer, the system with the superconducting DC transmission weighs 1.7 kg/kW (2.8 lbm/shp) (or 15 percent) less than the mechanical system with the gearbox; of the components which make up the "Subtotal" weight, all except the power conversion system are heavier in the mechanical system. The propulsion system with the SEGMAG electrical transmission weighs only .24 kg/kW (0.4 lbm/shp) (or 2.5 percent) more than the system with the superconducting DC electrical machines.

For the high-speed destroyer, the system with the mechanical transmission weighs .50 kg/kW (0.8 lbm/shp) (or 7 percent) less than the two systems with

DC electric transmissions. Although the bed plate and shafting are heavier on the mechanical system, this is more than counteracted by the weight of the mechanical epicyclic transmission. In the previous SEGMAG study (Ref. 1.18), the specific weight of the reduction gears for a twin-shaft destroyer propulsion system (at 29.8 MW (40,000 shp) per shaft) is 2.4 kg/kW (4 lbm/shp). If the present high-speed destroyer incorporated gears this heavy, the electrical transmission systems would have been lighter in overall weight.

1.3.3 Weight Breakdown

The payload of a ship with a given total displacement can be determined by subtracting the combined weight of the ship's structure, its propulsion system, and the fuel required for a specified mission from the total displacement. For the 59.7 MW (80,000 shp) conventional destroyer whose total displacement was assumed to be 7926 m tons (7800 L tons), the ship's structure is 45 percent or 3567 m tons (3510 L tons) of this displacement. The corresponding specific weights of the total propulsion systems are presented in Table 1.7, for the mechanical and electrical transmissions (both superconducting DC and SEGMAG). For the conventional destroyer, there are two missions of interest: a 200-hr. duty cycle, shown in Fig. 1.11, undertaken at an average speed of 10.3 m/s (20 knots); and a cruise mission of 3000 nautical miles undertaken at a constant speed of 10.3 m/s (20 knots). To calculate the fuel consumed during each of these missions, the curves of specific fuel consumption (sfc) presented in Fig. III-4 of Ref. 1.27 were used. For the systems with electrical tranmissions, the line labeled "Closed Cycle-Inventory Control" was used because it represents the minimum sfc of the CCGT. Its use is made possible because the electrical transmission allows the gas turbine to operate at the speed which provides the lowest fuel consumption for a given power level. For systems with mechanical transmissions,the sfc is degraded relative to the SFC for the electrical transmission. In this case, the SFC was obtained from Fig. III-4 of Ref. 1.27 by placing a curve between the line labeled "FT9 LM2500 Open Cycle" (which is non-regenerated) and the line labeled "Closed Cycle-Inventory Control." This curve causes the sfc to be greater than the minimum CCGT value by an amount equal to ten percent of the difference between the two curves just mentioned. This adjustment is necessary since the mechanical transmission will not allow the turbine to be operated at the speed corresponding to its lowest sfc for a given thrustor rpm. Use of these sfc curves, allows the amount of fuel consumed during a specific mission to be calculated directly. The efficiency of the mechanical transmission is 0.98, independent of load; the efficiency of the electrical transmission is 0.965, which is comprised of the generator efficiency (0.985) and the motor efficiency (0.985) and the motor efficiency (0.98), independent of load. These efficiencies are used to estimate the thrust required from the turbine. Then, knowing this amount of fuel, the payload can be reduced. Table 1.8 shows the weight breakdown of the conventional destroyer with three types of transmissions and two different missions; Fig. 1.12 is a

bar-chart comparison of the payloads. For either of the two missions, conventional destroyers with the electrical transmission, had a payload capability approximately 127 m tons (125 L tons) higher than that of the same vessel incorporating a mechanical transmission.

For the 119.4 MW (160,000 shp) high-speed destroyer, the total displacement is assumed to be 3556 m tons (3500 L tons) and the weight of the ship's structure is 44 percent of this displacement or 1565 m tons (1540 L tons). Again, the specific weights of the total propulsion systems are presented in Table 1.7. In the case of the high-speed destroyer, there are also two missions of interest: a 100-hr. duty cycle shown in Fig. 1.13, undertaken at an average speed of 16.3 m/s (31.6 knots); and a cruise mission of 5560 km (3000 nautical miles) undertaken at a constant of 10.3 m/s (20 knots). The calculation procedure used for the conventional destroyer was also used to estimate the fuel consumption of the high-speed destroyer. Table 1.9 shows the weight breakdown of the high-speed destroyer with the three types of transmissions and the two different missions; Fig. 1.14 is a bar-chart comparison of the payloads. For the cruise mission, the payload for the ship with the electrical transmission is 709 m tons (697 L tons), which is 28.5 m tons (28 L tons) (or 4 percent) more than for the ship with the mechanical transmission. However, for the 100-hr duty cycle mission, the payload for the ship with mechanical transmission is 355 m tons (349 L tons), which is 25.4 m tons (25 L tons) more (or 7 percent) than for the ship with the electrical transmission. The payload is greater on the ship with the mechanical transmission because the 58 m tons (57 L ton) weight of the mechanical transmission more than offsets the additional 32.5 m tons (32 L tons) more fuel consumed over the duration of the 100-hr duty cycle.

1.4 Advantages and Disadvantages of Electrical and Mechanical Transmissions

The potential advantages and disadvantages of electrical (both SEGMAG and superconducting) and mechanical transmission systems are identified for the lightweight propulsion system applications. Each of the three transmission systems has advantages and disadvantages relative to the other, and these are discussed in the sections which follow. In the past, the main advantages of a mechanical transmission have been considered to be a well-developed technology and lighter weight than that for conventional electrical equipment. The advent of lightweight superconducting and SEGMAG designs, however, can lessen or eliminate the weight advantage.

1.4.1 Advantages of Superconducting Electrical Transmissions

Superconducting electrical transmission systems have a number of advantages relative to mechanical transmissions. First, because the power transfer is by electrical cable, the prime mover (with the generator) can be located remotely from the motor-thrustor drive. Further, the prime mover does not have to be

aligned with the thrustor, and the turbine shaft does not have to be at the same angle as the thrustor shaft. Second, with electrical switchgear, the direction of shaft rotation can be reversed electrically while operating at full power. This reversing feature means that a fixed-pitch propeller rather than a controllable-reversible-pitch propeller can be used. Third, cross-connections are practical with an electric transmission on a multiturbine vessel. Electrical cross-connections allow one prime mover to supply power to two or more thrustors. Hence, there is the option of using a smaller number of turbines running at a higher percentage of full power and hence better specific fuel consumption (sfc), rather than using all the turbines at a lower percentage of full power and poorer sfc. This ability to electrically cross-connect the turbine generators to the thrustors can also result in higher mission success rates, because the actual operating time of each turbine on a mission is reduced. Further, the reliability of the propulsion system is improved because either turbine can drive both shafts. Fourth, with an electric transmission, the input/output speed ratio can be continuously varied, and a wide range of effective gear ratios is achievable by changing the magnetic field excitations in the electrical motors and generators. Fifth, with an electric transmission, rapid deceleration of the ship from high speeds can be enhanced by allowing the motor to operate as a generator and then dissipating energy in electrical resistors. These resistors can also minimize the problem of possible turbine overspeed. Sixth, an electrical transmission system is potentially quieter than a mechanical system, because the noise is primarily aerodynamic rather than mechanical. Seventh, an electrical transmission is potentially lighter, because the electrical transmission is currently much less developed than mechanical systems, and large advancements could yet be made to reduce the specific weight of electrical transmissions still further.

1.4.2 Advantages of SEGMAG Electrical Transmissions

The advantages cited above are common to both SEGMAG and superconducting transmissions, but transmissions with SEGMAG machinery have an additional important advantage. SEGMAG transmissions are less complex (Ref. 1.30) than those with superconducting machines in three areas. First, SEGMAG machines use graphite brushes to collect the current, in contrast to the more complex liquid metal current collectors in superconducting machines. Second, SEGMAG machines do not require the helium liquifiers that superconducting machines require. Third, SEGMAG machines do not have superconducting coils that must be protected in case of a large transient. If the magnetic flux becomes too high, then the coil would lose its superconductivity and melt with the high current and the non-zero resistance.

1.4.3 Disadvantages of SEGMAG Electrical Transmissions

SEGMAG transmissions have one disadvantage relative to mechanical transmissions. A mechanical gearbox could presumably run when flooded, but

the problem of avoiding electrical short-circuits in a flooded electrical transmission would present a more severe operating condition.

1.4.4 Disadvantages of Superconducting Transmissions

In addition to vulnerability to flooding, superconducting electrical transmissions have several disadvantages relative to both SEGMAG and mechanical transmissions. First, superconducting electric transmissions require a cryogenic subsystem to supply liquid helium and liquid nitrogen. This extra equipment adds to the overall system cost and maintenance requirements, and the overall system reliability may be lowered because of this additional subsystem. Further, highly-skilled sailor/technicians may be required to operate and service the cryogenic equipment. Second, with superconducting electrical machinery, the long cooldown time of the cryogenic parts of the system must be scheduled appropriately, because the start-up procedures for superconducting electrical machines are lengthy and complicated. This problem does not exist with SEGMAG machines.

1.4.5 Advantages of Mechanical Transmissions

Mechanical transmission systems have advantages in a number of areas. First, mechanical transmissions are based on proven technology, and the state-of-the-art of mechanical transmissions is more advanced relative to that of lightweight electrical transmissions. Mechanical transmissions have been used in ship propulsion for years, and the technology is proven and accepted. Because of this state-of-the-art, overall development costs required for the lightweight propulsion system application will be less than those of electrical transmissions where the state-of-the-art is still far from large-scale commercial implementation. Second, mechanical transmissions require only conventional maintenance procedures which can be handled by experienced mechanics. In contrast, the maintenance of superconducting electrical transmissions would be significantly more complex and would require personnel specially trained in cryogenics. Third, mechanical transmissions are compatible with existing auxiliary components. For example, oil pump drives can be incorporated with the mechanical transmission by extracting the needed shaft power directly from the gears inside the transmission. Fourth, mechanical transmissions should be expected to have better shock resistance than electrical transmissions because of rugged structure and the absence of delicate electric conductors and insulation.

1.4.6 Disadvantages of Mechanical Transmissions

Mechanical transmission systems also have a number of inherent disadvantages. First, precision alignment of the mechanical transmission between the shafts of the engine and the thrustor is required. Even with this alignment, a flexible coupling may still be required to allow for vibration and for minor misalignment. Second, an inherent characteristic of mechanical transmissions is that mechanical clutches are required. Third, mechanical transmissions have fixed gear ratios,

and once the transmission has been designed, the gear ratio cannot be changed and power conversion system efficiency compromises will result. Fourth, mechanical transmissions tend to be bulky, because they are monolithic and are not composed of components that can be easily assembled in place on the ship.

1.5 Impact of Electrical Transmissions on Ship Design

The use of an electrical transmission instead of a mechanical transmission in a naval propulsion system has a number of effects on the design and operation of the ship.

1.5.1 Impact on Ship Design

One effect on ship design associated with the use of an electrical transmission (either SEGMAG or superconducting) is the significantly greater flexibility possible in the layout of the shipboard components. Because the prime mover (with the generator) can be located remotely from the motor-thrustor drive, the prime mover can be placed in a less critical area of the ship and/or can be located to help achieve better ship stability. This flexibility may also result in reduced ducting between the heater or boiler inlet and the power conversion system components. Another result of the increased flexibility is that the vulnerability of the ship is reduced, because the components of the propulsion system are more dispersed and yet their operation is more versatile because of electrical cross-connectability. Another impact of the electrical transmission on ship design is that a lighter thrustor can be used, because the electric transmission is electrically reversible and does not require reversing gears or thrustor components. For example, when controllable-reversible-pitch propellers (which are usually heavier than fixed pitch propellors) are required, the diameter and wall thicknes of the shafting must often be increased to support a heavier thrustor and allow passage of internal linkages.

With an electrical transmission, electrical resistors can be used to dissipate the energy generated during deceleration preparatory to ship reversal. During gradual deceleration, the motor can function as a generator and the electricity thereby produced is dissipated in a resistor bank. During emergency deceleration, the resistors can also be used to absorb excess generator capacity. These resistors are water-cooled so the full current rating can be continuously dissipated without overheating and melting during prolonged periods of successive reversals. Hence, provision to water cool this braking resistor must be included in the ship's design.

1.5.2 Impact on Installation

The use of an electrical transmission also has an impact on installation. Because the electrical system consists of a number of smaller components in contrast to the monolithic mass of the mechanical gearbox, the electrical

transmission is easier to install with the smaller (but more numerous) components being assembled on board. For a superconducting transmission, another consideration is that space must be assigned for the cryogenic system which will supply liquid helium and liquid nitrogen. The cryogenic system must supply both the motor and the generator, and heavily insulated supply lines will be required. The length of these lines will depend on how remotely the motor is situated from the generator.

1.5.3 Impact on Operation

With the cross-connectability feature of electric transmissions, the overall reliability of the ship's operation is enhanced. If a problem should arise in one of the turbine-generator sets, then the other turbine-generator set can be electrically switched into the circuit to drive both thrustors. Even during normal part-power operation, one turbine (instead of two turbines operating at lower power) can be used to power both thrustors. This means that the statistical availability of the overall propulsion system can be increased, because the actual accumulated operating time of each turbine on a given mission can be reduced. Further, because low power operation occurs for a significant portion of the duty cycle, this type of operation produces better fuel economy by allowing the gas turbine to operate closer to peak efficiency and thereby provide a greater range for a given amount of fuel, or a heavier payload for a fixed range.

The variability of the speed ratio between the turbine and thrustor which is possible with electric transmissions, allows the turbine to be operated at the most efficient shaft speed at a given power. Hence, specific fuel consumption is improved. And when maneuvering in close quarters, the low propeller speeds required can be obtained by electrically adjusting the effective gear ratio.

The cooldown time required during start-up (if the electrical transmission uses superconducting electrical machines) can have a significant effect on the combat readiness of Naval vessels. For example, for the superconducting AC machines considered by Greene in Ref. 1.7, a time period of 20 hours was estimated as required to cool the equipment from ambient down to liquid helium temperatures of 4.2 K. To avoid this excessive time, Greene suggested that the rotors of the electrical machines be kept at or near superconducting temperatures when the propulsion system is on standby. (Although the same type of cooldown problem would exist with superconducting DC machines, this problem does not exist with SEGMAG electrical machines.) Operational practices, and even the total fuel required, would thus be affected.

1.5.4 Impact on Other Components

The use of an electrical transmission has an effect on several other ship requirements and components. As discussed above, an electrical resistor bank

with water cooling must be carried to dissipate energy generated during decelerations. The thrustor design and auxiliary requirements are also affected. With an electric transmission, a fixed-pitch (FP) propeller rather than a controllable-reversible-pitch (CRP) propeller can be used. An FP propeller has a number of advantages relative to a CRP propeller. These include: (1) simpler maintenance (because much of the reversing mechanism is outboard with a CRP propeller, and dry docking would be required for repairs and maintenance); (2) lower noise; (3) potentially higher efficiency because of the smaller hub diameter; (4) lack of a complicated servo-mechanism as required to move the blades on a CRP propeller. Further, both the FP propeller and the shafting can be lighter than the CRP propeller and shaft subsystems.

In Phase III-2, a number of potential ship arrangements are considered. As seen there, the positioning of the generators, motors, and refrigeration equipment (if required) can have a significant effect on the utilization of ship volume. The effect of positioning components on ship design is also considered in Phase III-2 along with the other factors discussed in this section and section 1.4.

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TABLE 1.1

AVAILABLE EFFICIENCY DATA ON SUPERCONDUCTING DESIGNS

Description	Design Point Values			Source
	Rating HP (MW)	Speed RPM	Full-Load Efficiency %	
DC Hexapole Motor	40,000 (29.8)	180	98.0	Stevens et al. (Ref. 1.11)
DC Quadrupole Motor	40,000 (29.8)	180	98.3	Stevens et al (Ref. 1.11)
DC Homopolar Motor	40,000(29.8)	180	97.76	Stewart (Ref. 1.12)
DC Homopolar Generator	20,000 (14.9)	3300	99.29	Stewart (Ref. 1.12)
AC Synchronous Motor	25,000 (18.6)	1200	99.3	Thompson et al. (Ref. 1.8)
AC Synchronous Generator	17,500 (13)	6000	99.5	Thompson et al. (Ref. 1.8)
AC Synchronous Generator	6,700 (5)	3600	98.5	McCann and Mole (Ref. 1.9)
AC Synchronous Generator	26,800 (20)	3600	98.1	Glebov et al. (Ref. 1.6)
AC Synchronous Generator	671,000 (500)	3600	98.8	Appleton and Anderson (Ref. 1.4)
*AC Synchronous Generator	4030 (3)	3600	98.0	Smith et al. (Ref. 1.25)

* **Experimentally Measured Efficiency**

TABLE 1.2

EFFICIENCY DATA ON SELECTED NON-SUPERCONDUCTING EQUIPMENT

Type	Design Point Values: Rating HP (MW)	Design Point Values: Speed RPM	Efficiency (%): Full-Load	Efficiency (%): 3/4-Load	Efficiency (%): ½-Load	Efficiency (%): 1/4-Load	Source
SEGMAG DC Motor	40,000 (29.8)	168	97.86	-	97.96	97.28	Feranchak et al (Ref. 1.18)
SEGMAG DC Generator	26,300 (19.6)	3600	98.76	-	98.48	98.71	↓
SEGMAG Transmission Lines	-	-	99.97 (6 m Bus)	-	99.97	99.86 (37 m Cross-Connect)	
AC Synchronous Motor	4,000 (2.98)	150	95.0	95.6	94.9	-	Mark's Handbook (Ref. 1.26)

TABLE 1.3

ESTIMATED WEIGHTS AND SIZES OF SUPERCONDUCTING DC MOTORS
AT SELECTED POWERS AND SPEEDS

MW	Power (HP)	Speed RPM	Full-load Torque Factor kW/RPM	Weight kg	Vol m^3	Dia m	Length m
14.9	(20,000)	320	47	17,800	6.2	1.7	2.7
29.8	(40,000)	230	130	38,200	12.5	2.2	3.4
29.8	(40,000)	980	31	13,200	4.7	1.5	2.5
59.6	(80,000)	160	370	83,900	25.5	2.7	4.4
59.6	(80,000)	580	103	31,800	10.6	2.0	3.2

TABLE 1.4

ESTIMATED WEIGHTS AND SIZES OF SUPERCONDUCTING DC GENERATORS
AT SELECTED POWERS AND SPEEDS

MW	Power (HP)	Speed RPM	Full-load Torque Factor kW/RPM	Weight kg	Vol m^3	Dia m	Length m
14.9	(20,000)	3600	4.1	5,910	1.1	1.1	1.3
29.8	(40,000)	3600	8.2	10,000	1.9	1.3	1.5
59.6*	(80,000)	3600	16.4	17,300	3.2	1.5	1.8
59.6**	(80,000)	3000	20.1	20,000	3.8	1.6	1.9

* Design above Magnetic Flux Density limit; Therefore risky

** Design at Magnetic Flux Density Limit; Therefore possible

TABLE 1.5

ESTIMATED WEIGHTS AND SIZES OF SEGMAG DC MOTORS

Power MW (HP)	Speed RPM	Full-Load Torque Factor KW/RPM	Weight kg	Volume m^3	Dia m	Length m
14.9 (20,000)	320	47	20,000	7.4	2.4	1.7
29.8 (40,000)	230	130	42,700	14.7	3.0	2.1
29.8 (40,000)	980	31	14,500	5.7	2.2	1.5
59.6 (80,000)	160	370	95,500	29.2	3.8	2.6
59.6 (80,000)	580	103	35,500	12.5	2.8	2.0

TABLE 1.6

ESTIMATED WEIGHTS AND SIZES OF SEGMAG DC GENERATORS

Power MW (HP)	Speed RPM	Full-Load Torque Factor KW/RPM	Weight kg	Volume m^3	Dia m	Length m
14.9 (20,000)	3600	4.1	8,200	1.3	0.91	2.0
29.8 (40,000)	3600	8.2	14,100	2.2	1.07	2.3
59.6 (80,000)	3600	16.4	24,100	3.7	1.28	2.8
59.6 (80,000)	3000	19.8	27,300	4.1	1.34	2.9

TABLE 1.7

PROPULSION SYSTEM WEIGHTS FOR CONVENTIONAL AND HIGH-SPEED DESTROYER INSTALLATIONS

	Conventional Destroyer CCGT	High Speed Destroyer CCGT
Speed, Max./Cruise, m/s (knots)	18/10 (35/20)	26/10 (50/20)
Displacement, m ton (long tons)	7926 (7800)	3556 (3500)
Installed Power, MW (shp)	59.7 (80,000)	119.4 (160,000)
Displacement/Power, kg/kW (lbm/shp)	132.3 (218)	29.8 (49)
Total Structure/Displacement	0.45	0.44
Structure Sp. Wt., kg/kW (lbm/shp)	59.8 (98.3)	13.1 (21.6)

Number of Thrustors		2			2	
Thrustor Speed, RPM		230			580	
Type of Thrustor	CRP	FP	FP Electr.	FP	FP	FP Electr.
Type of Transmission	Mech	Electr. S/C DC	SEGMAG	Mech	Electr. S/C DC	SEGMAG
Propulsion System Sp. Wt., kg/kW (lbm/shp)						
"Wet" Power Conversion System	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)
Bed Plate	.87 (1.43)	.58 (0.95)	.58 (0.95)	.87 (1.43)	.58 (0.95)	.58 (0.95)
Transmission	2.24 (3.69)	2.07 (3.40)	2.25 (3.70)	.53 (0.87)	1.34 (2.20)	1.36 (2.24)
Shafting - Inboard	.58 (0.95)	.19 (0.32)	.19 (0.32)	.21 (0.35)	.12 (0.19)	.12 (0.19)
- Outboard	.74 (1.22)	.74 (1.22)	.74 (1.22)	.30 (0.49)	.26 (0.42)	.26 (0.42)
Thrustor	.94 (1.54)	.49 (0.80)	.49 (0.80)	.09 (0.14)	.09 (0.14)	.09 (0.14)
Subtotal	6.67 (10.97)	5.37 (8.83)	5.55 (9.13)	3.30 (5.42)	3.69 (6.04)	3.71 (6.08)
Others	2.00 (3.29)	1.61 (2.65)	1.67 (2.74)	.99 (1.63)	1.10 (1.81)	1.11 (1.82)
Heater Systems	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)
Total Weight	11.31 (18.61)	9.62 (15.83)	9.86 (16.22)	6.93 (11.40)	7.43 (12.20)	7.46 (12.25)

TABLE 1.8

WEIGHT BREAKDOWN OF CONVENTIONAL DESTROYER
. given in metric tons (long tons)

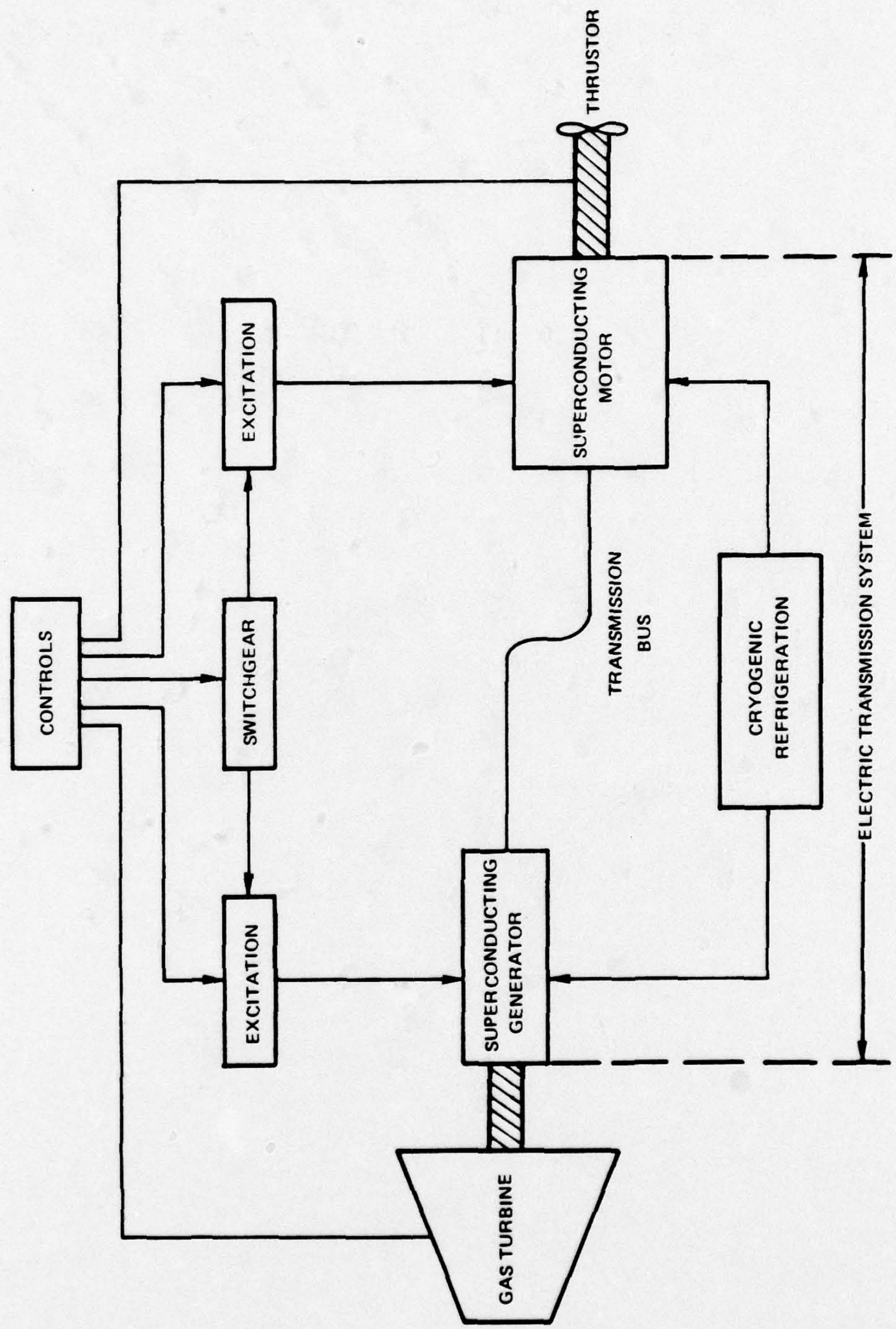
Mission	Cruise 3000 Nautical Miles at 20 Knots			200-Hr Duty Cycle		
Types of Transmission	Mech.	S/C DC Electr.	SEGMAG DC Electr.	Mech.	S/C DC Electr.	SEGMAG DC Electr.
Total Displacement	7926 (7800)	7926 (7800)	7926 (7800)	7926 (7800)	7926 (7800)	7926 (7800)
Structure	3567 (3510)	3567 (3510)	3567 (3510)	3567 (3510)	3567 (3510)	3567 (3510)
Propulsion System	652 (642)	551 (543)	565 (556)	652 (642)	551 (543)	565 (556)
Amount of Fuel for Mission	358 (352)	331 (326)	331 (326)	590 (581)	560 (551)	560 (551)
Payload	3349 (3296)	3476 (3421)	3463 (3408)	3117 (3067)	3248 (3196)	3235 (3183)
Payload as % of Total Displacement	42.2	43.9	43.7	39.3	41.0	40.8

TABLE 1.9

WEIGHT BREAKDOWN OF HIGH-SPEED DESTROYER
. given in metric tons (long tons)

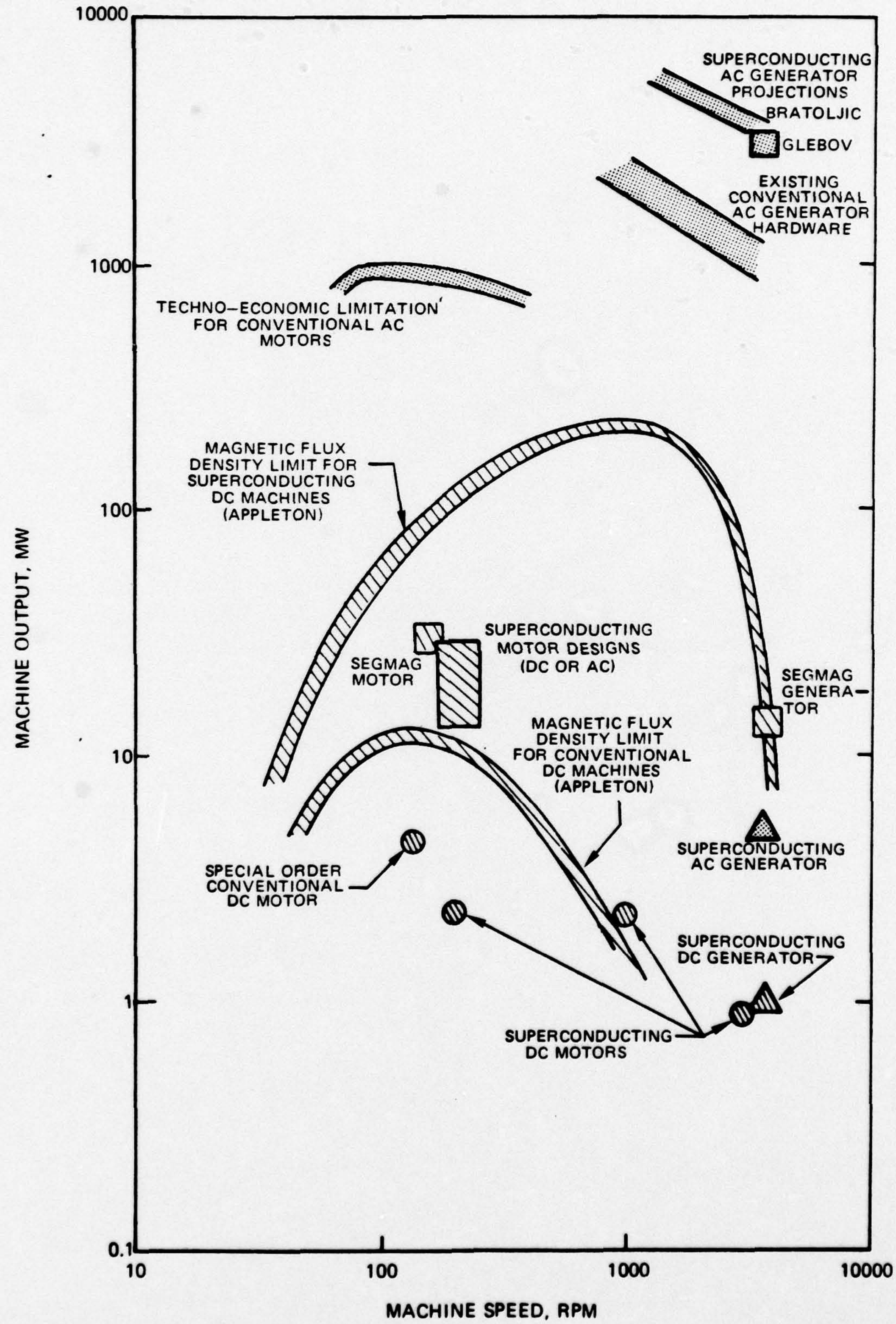
Mission	Cruise 3000 Nautical Miles at 20 Knots			100-Hr Duty Cycle		
Types of Transmission	Mech.	S/C DC Electr.	SEGMAG DC Electr.	Mech.	S/C DC Electr.	SEGMAG DC Electr.
Total Displacement	3556 (3500)	3556 (3500)	3556 (3500)	3556 (3500)	3556 (3500)	3556 (3500)
Structure	1565 (1540)	1565 (1540)	1565 (1540)	1565 (1540)	1565 (1540)	1565 (1540)
Propulsion System	761 (749)	819 (806)	822 (809)	761 (749)	819 (806)	822 (809)
Amount of Fuel for Mission	551 (542)	464 (457)	464 (457)	876 (862)	843 (830)	843 (830)
Payload	680 (669)	709 (697)	705 (694)	355 (349)	330 (324)	326 (321)
Payload as % of Total Displacement	19.1	19.9	19.8	10.0	9.3	9.2

SCHEMATIC OF SUPERCONDUCTING ELECTRIC TRANSMISSION SYSTEM



79-01-307-1

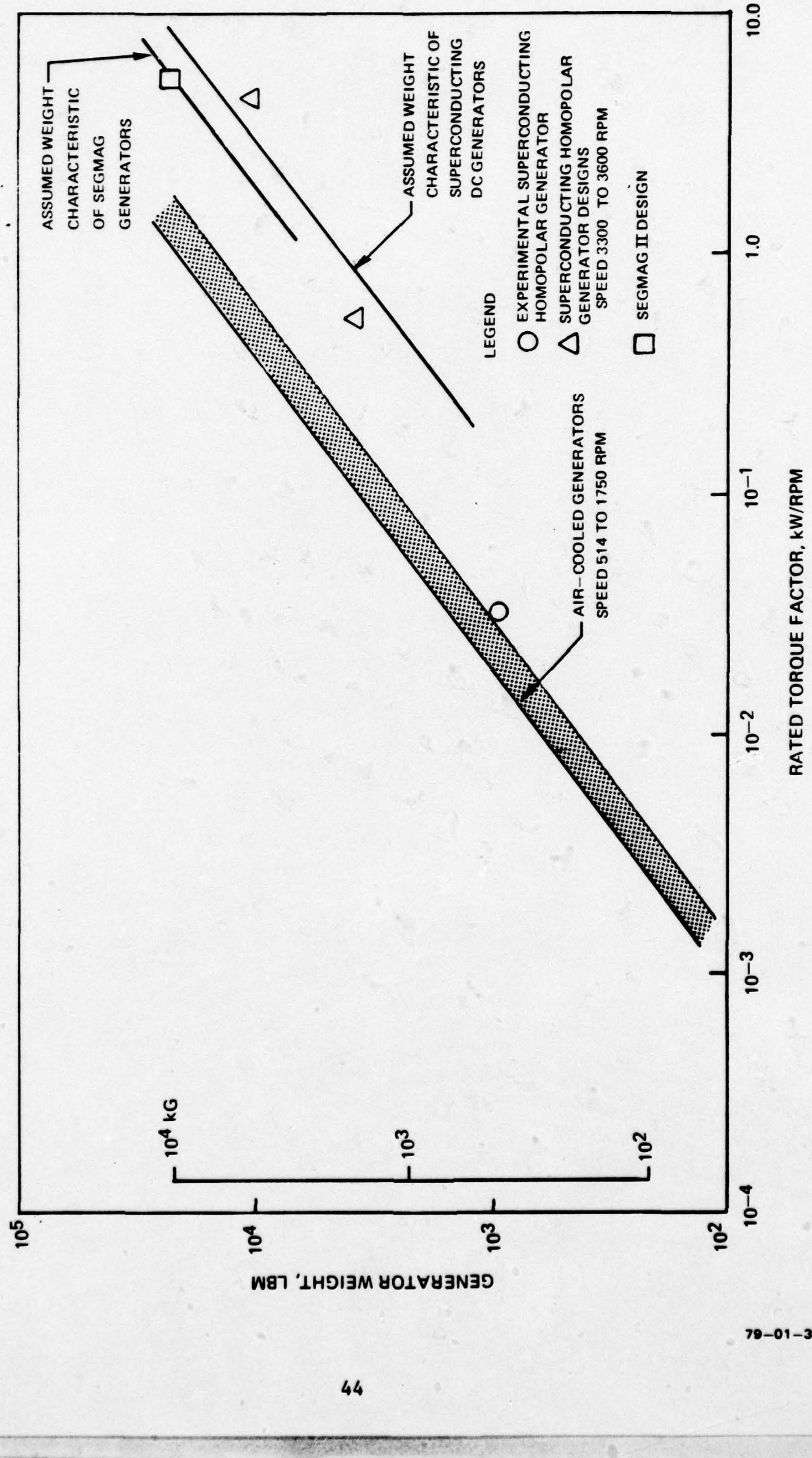
CAPACITY LIMITS OF ROTATING ELECTRICAL MACHINES



79–01–87–2

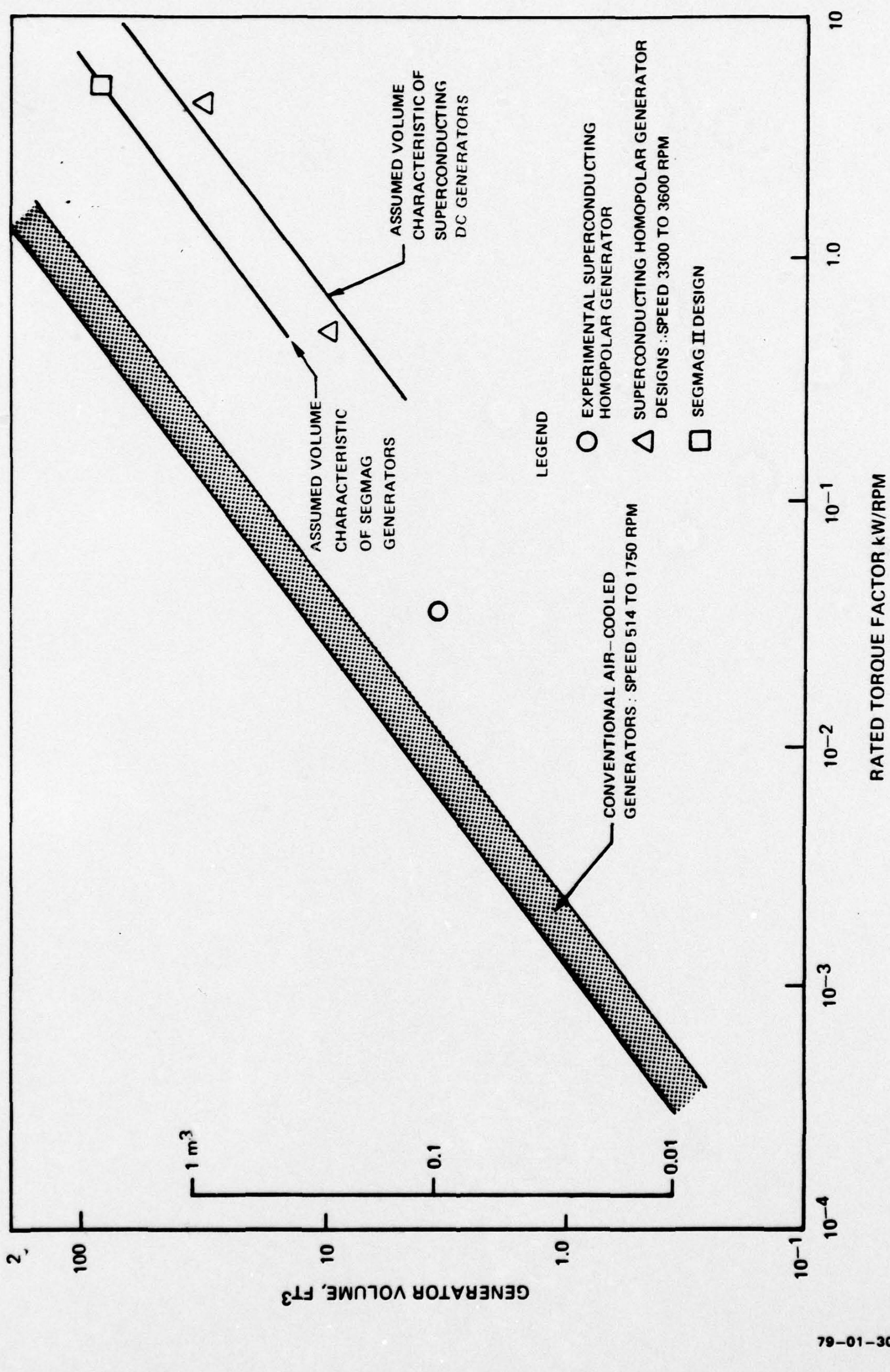
FIG. 1.3

WEIGHT CHARACTERISTICS OF DC GENERATORS



79–01–307–5

VOLUME CHARACTERISTICS OF DC GENERATORS



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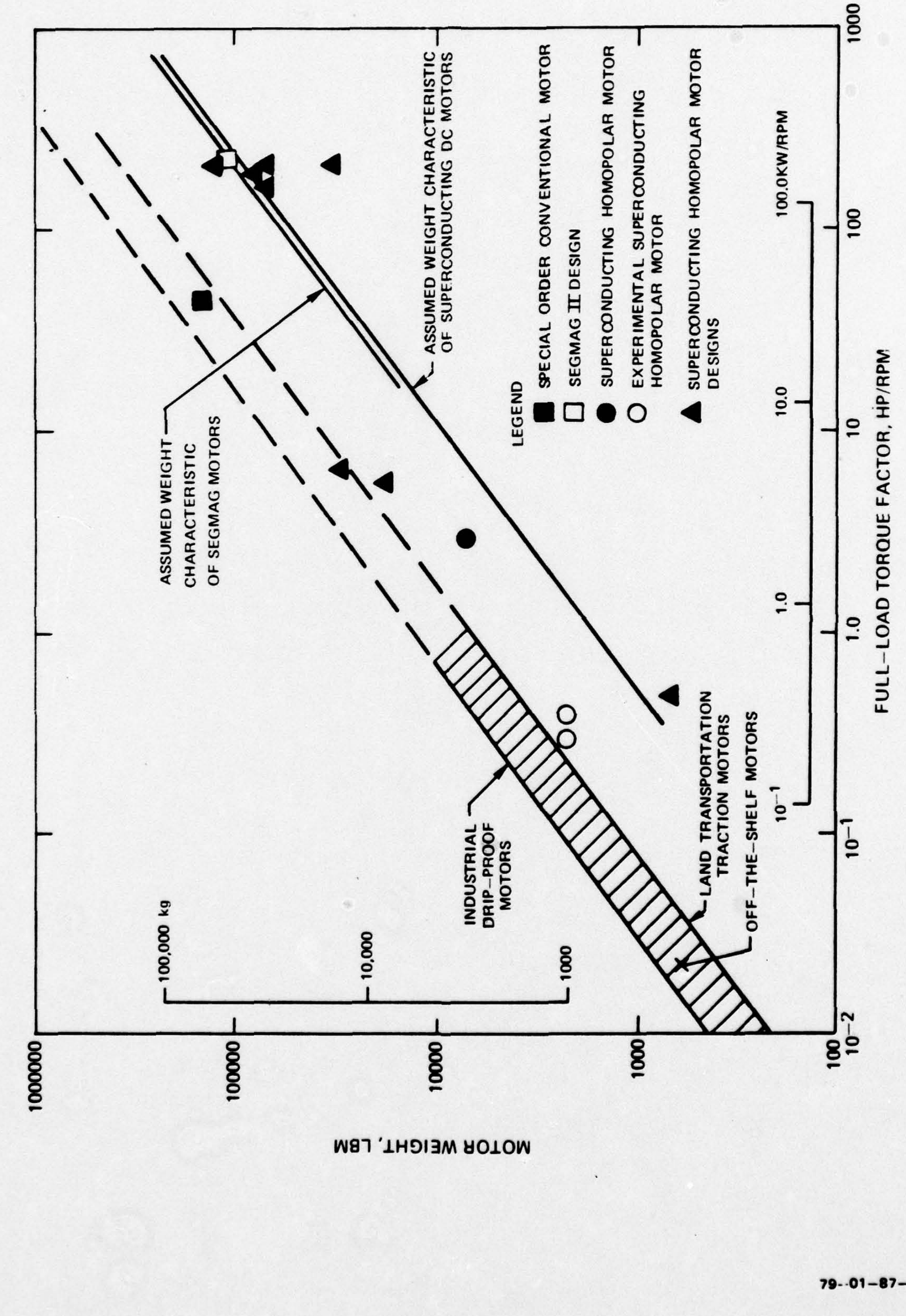
DC MOTOR WEIGHT CHARACTERISTICS



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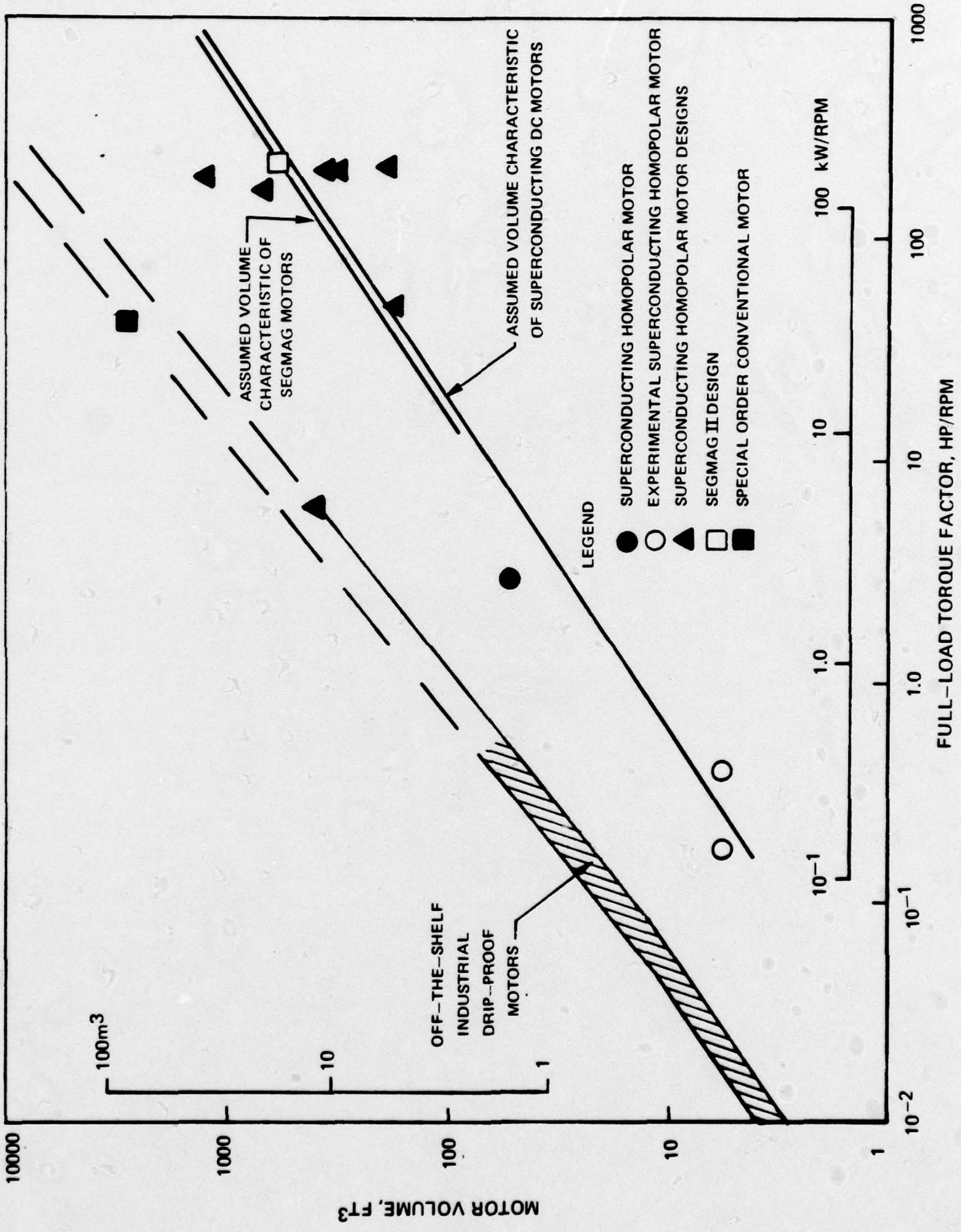
VOLUME CHARACTERISTICS OF DC MOTORS



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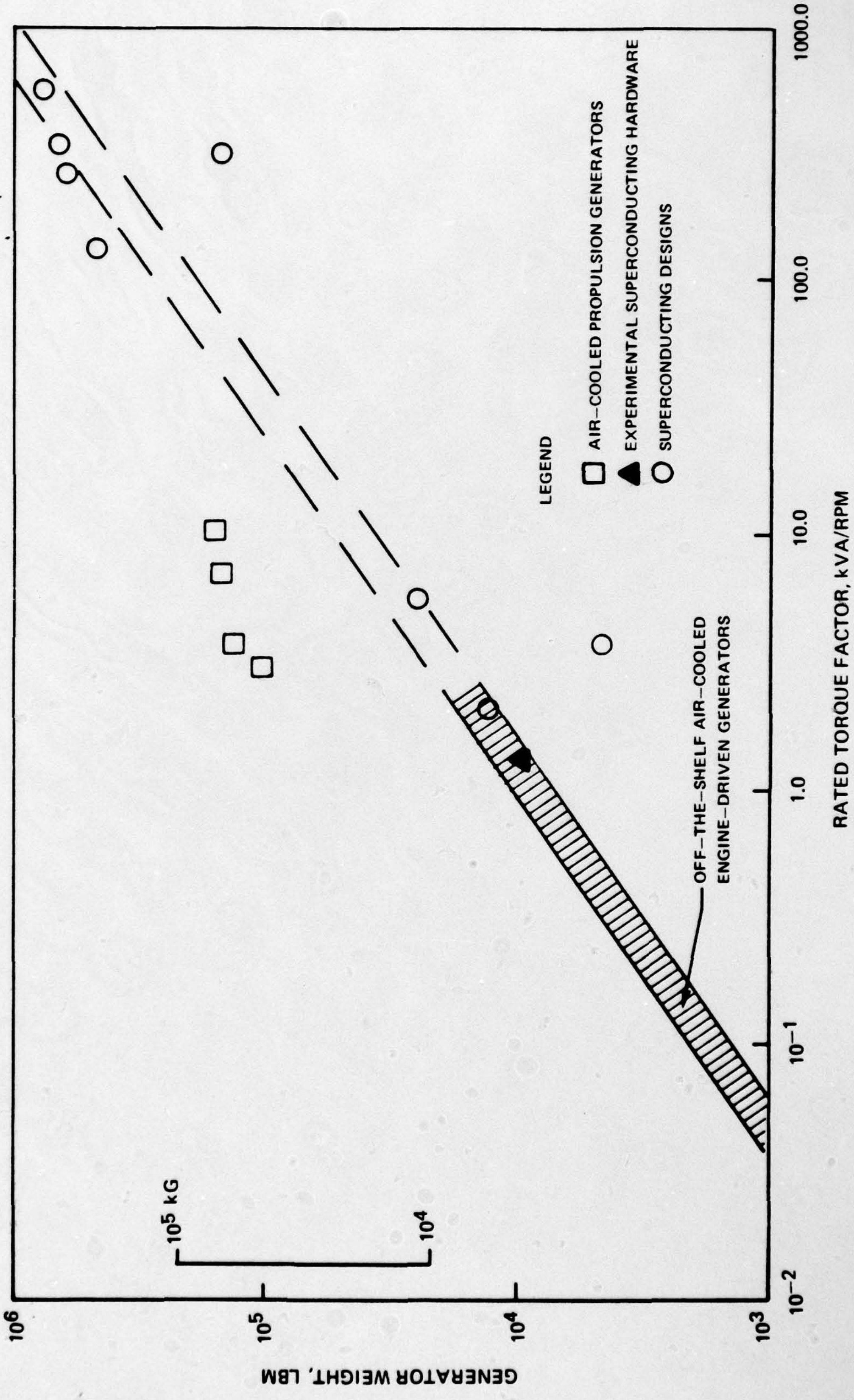
WEIGHT CHARACTERISTICS OF AC SYNCHRONOUS GENERATORS



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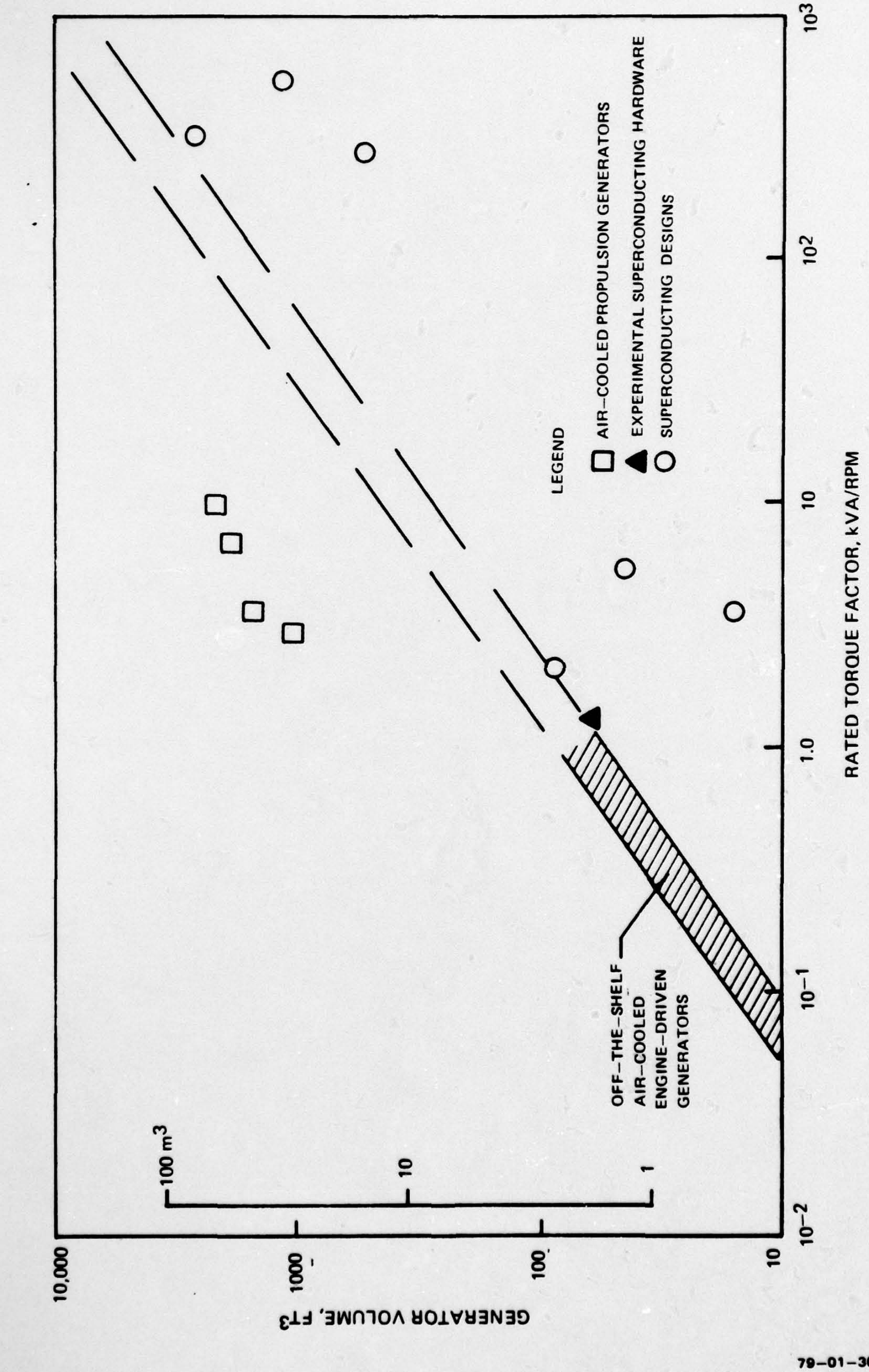
VOLUME CHARACTERISTICS OF AC SYNCHRONOUS GENERATORS



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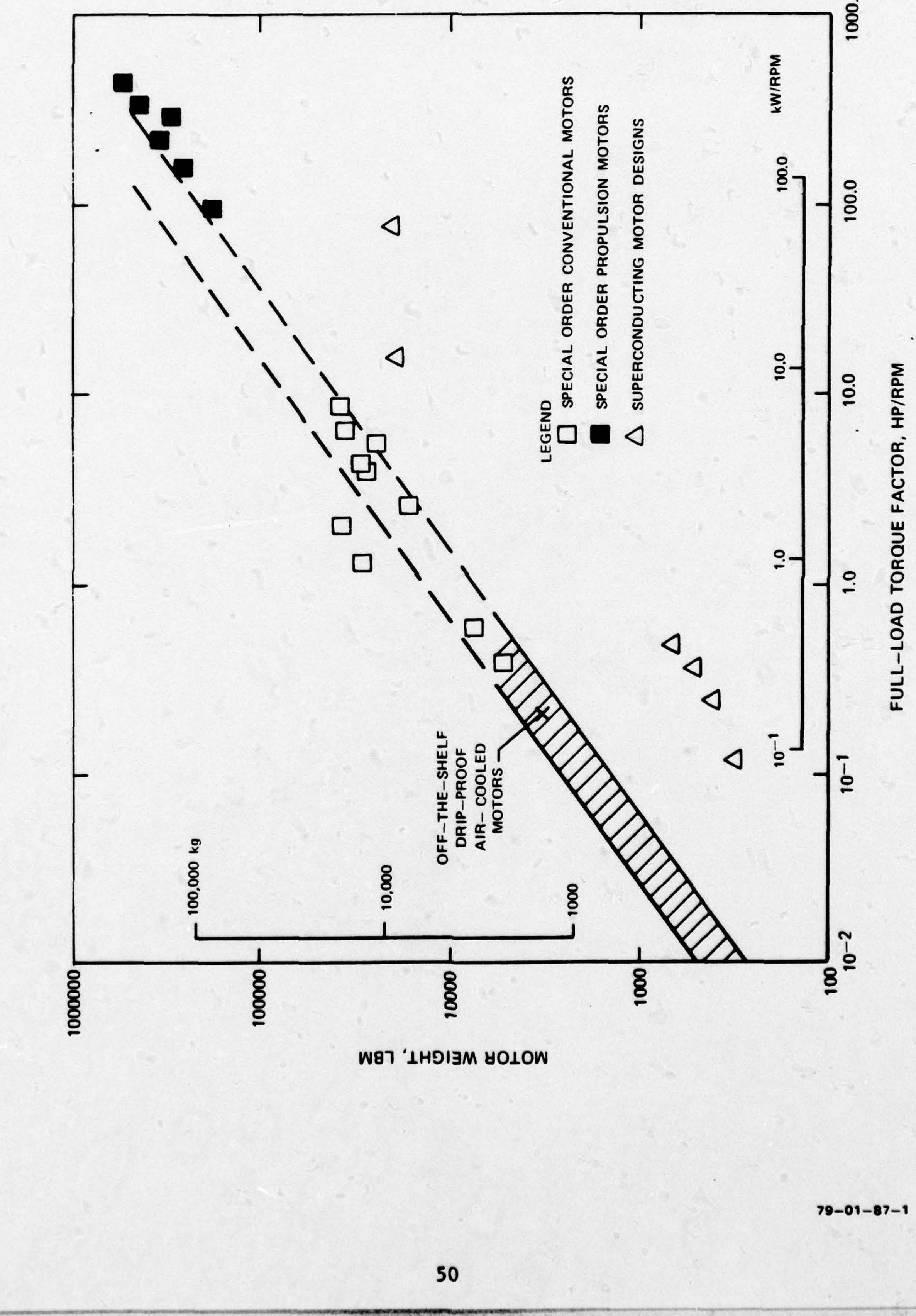
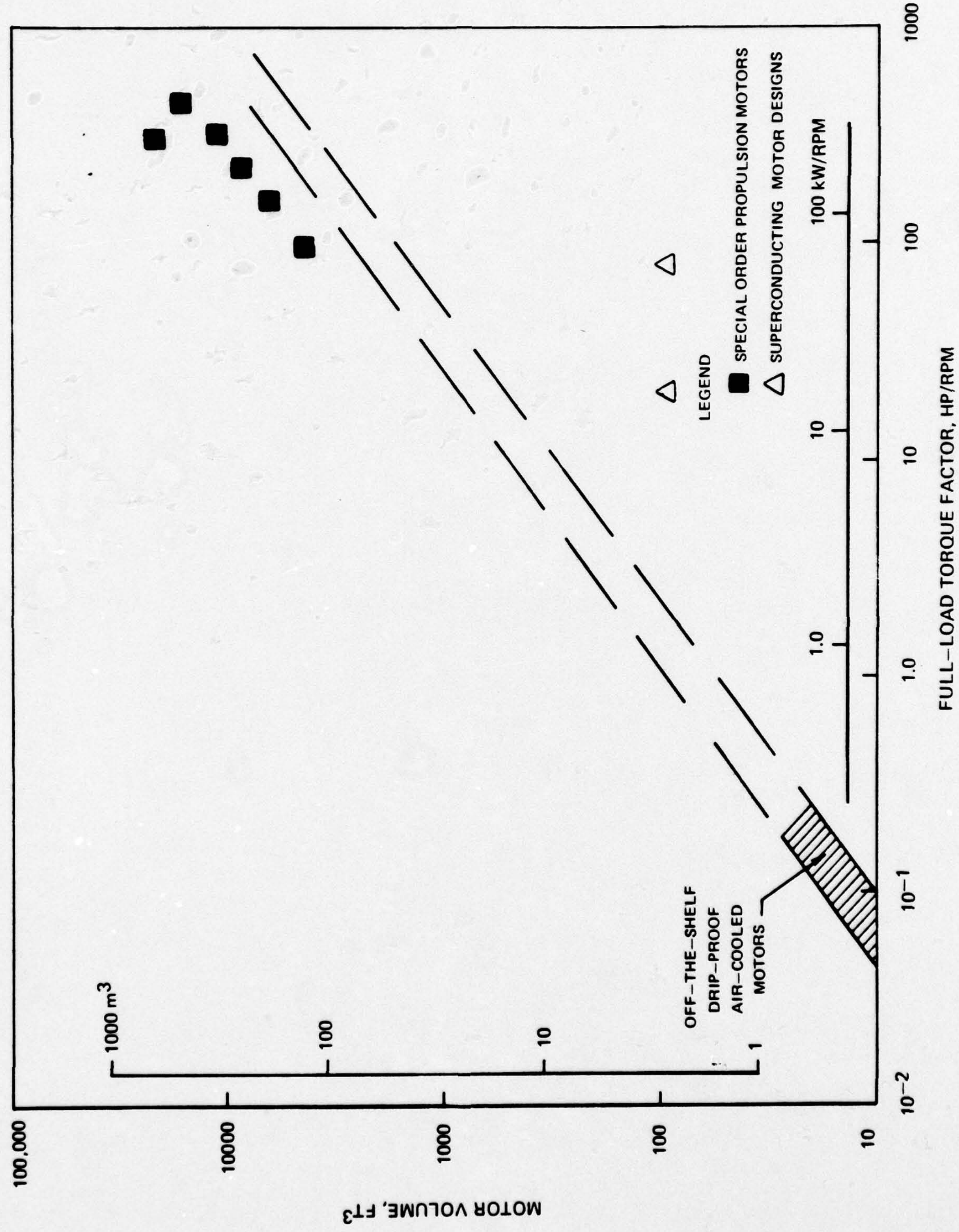
AC SYNCHRONOUS MOTOR WEIGHT CHARACTERISTICS



79-01-87-1

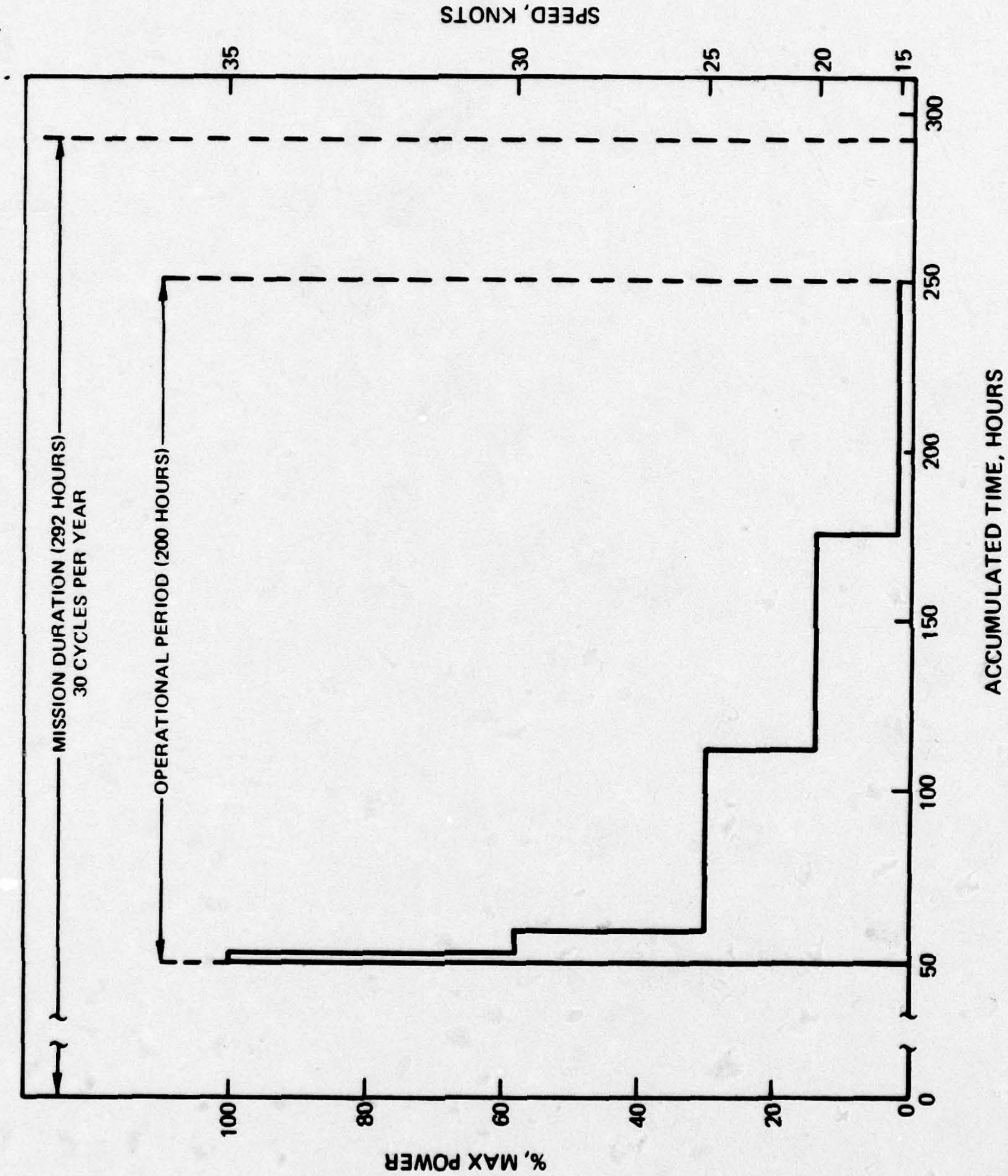
FIG. 1.10

VOLUME CHARACTERISTICS OF AC SYNCHRONOUS MOTORS



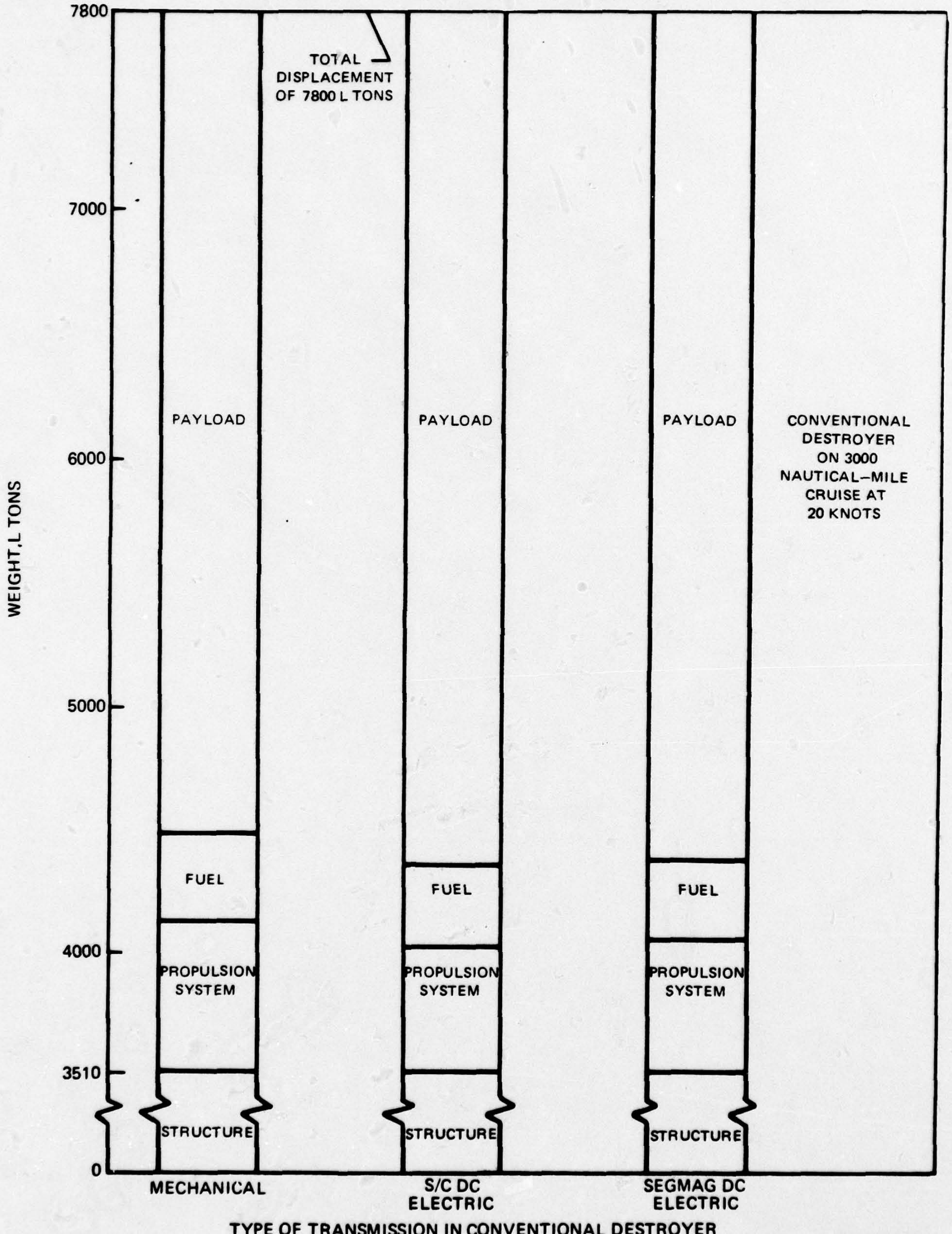
79-01-307-7

SELECTED CONVENTIONAL DESTROYER MISSION



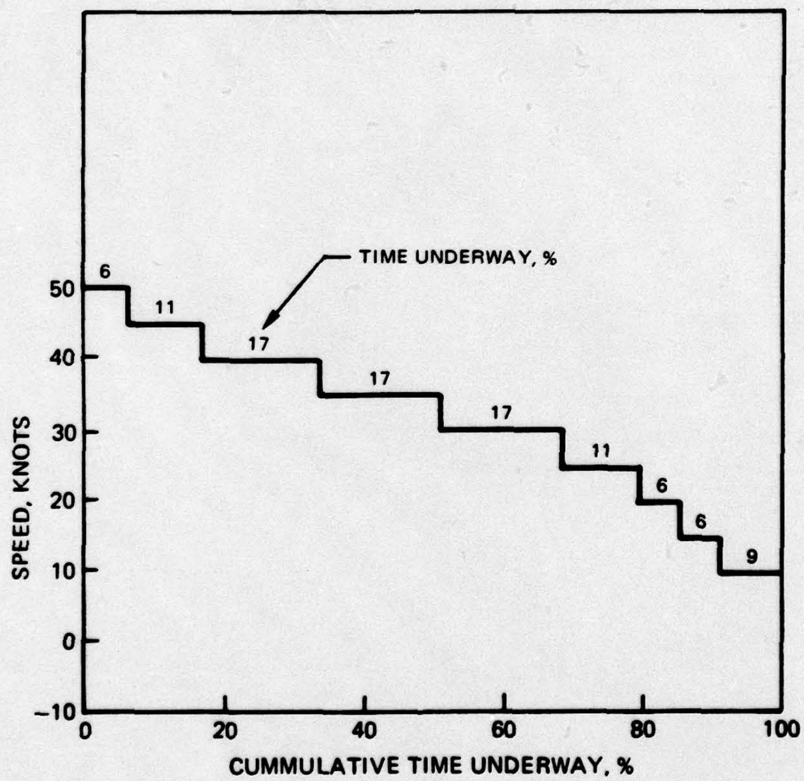
79–06–153–7

BAR CHART OF WEIGHT BREAKDOWN
FOR CONVENTIONAL DESTROYER



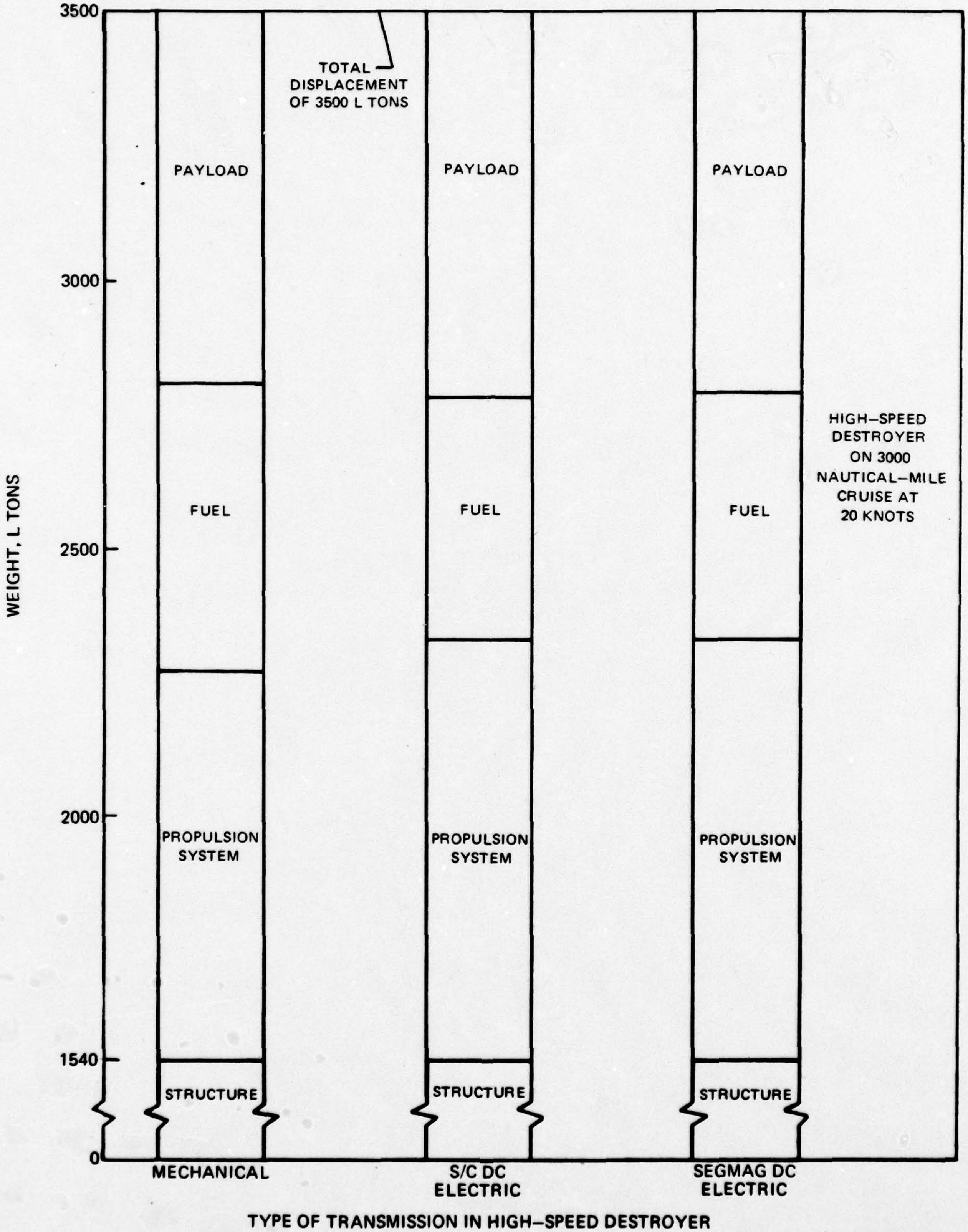
79–06–153–5

HIGH-SPEED DESTROYER DUTY CYCLE



79-06-153-8

BAR CHART OF WEIGHT BREAKDOWN
FOR HIGH–SPEED DESTROYER



79–06–153–6

PHASE III-2

COMPARATIVE EVALUATION OF PROPULSION SYSTEM CONFIGURATIONS

The objective of this phase of study is to compare the technical and economic merits of alternative propulsion system configurations which integrate the previously designed lightweight closed-cycle gas turbine propulsion engine with different types of mechanical and electrical transmissions and thrusters. In the sections which follow, twelve selected candidate alternative propulsion systems are characterized and the results of a comparative evaluation are presented. Based on the component technologies projected to become available in the 1990's and using a set of evaluation criteria selected, a comparative evaluation of the alternative propulsion system configurations has identified that the propulsion system (two needed) which employs the reference propulsion engine integrated with either an epicyclic reduction gearbox or a SEGMAG DC generator-motor set driving a supercavitating propeller would offer the highest potential for future high-speed destroyer applications; and that an electrical-drive propulsion system which consists of the reference propulsion engine driving two SEGMAG DC generator-motor sets would be preferable for conventional destroyers.

2.1 Schematic Diagrams of Alternative Propulsion Systems

Alternative propulsion systems considered in this study include those with both mechanical and electrical transmission systems (Fig. 2.1). These alternatives are derived from the results of: (1) the conceptual design of the 80,000-shp (59.7 MWe), fossil-fired, closed-cycle helium gas turbine (CCGT) system (Ref. 2.1) performed in Part II of the present study program; (2) the characteristics of mechanical transmission systems presented in Ref. 2.2 (Part I of this study); and (3) the characteristics of electrical transmission systems discussed in Phase III-1 of this report. Two advanced naval ship types which have been judged to benefit from use of the reference propulsion engine were selected as reference ships to evaluate the attractiveness of these alternative propulsion systems. These two reference ships, shown in Figs. 2.2 and 2.3 are: (1) a high-speed destroyer (HSD) with installed power of 160,000-shp (119.4 MW) and max/cruise speed of 50/20 knots (72/29 km/hr); and (2) a conventional destroyer (similar to Spruance-class vessels) with installed power of 80,000-shp (59.7 MW) and max/cruise speed of 35/20 knots (50/29 km/hr). The propulsion system alternatives would allow either ship type to be propelled by two or four thrusters. A single-thruster concept was ruled out since it was regarded as not being acceptable from the vulnerability viewpoint for the sizes of ships considered. The configuration using three thrusters was also ruled out because of the unusually complicated transmission system designs, operational requirements, and component interface problems aboardship.

In an effort to identify the most appropriate match between the ship types and transmission systems, a preliminary screening process was necessary. The results of this process are shown in Fig. 2.4. In the left column of Fig. 2.4 are shown the eight potential transmission system configurations selected for evaluation; these include two mechanical and six electrical transmissions. For the mechanical transmission systems, epicyclic and offset reduction gearboxes were considered. The former would use one input and one output shaft, whereas the latter would use one input and two output shafts. For the electric transmission systems, six configurations were considered: two use advanced segmented magnet (SEGMAG) DC machinery; two use superconducting (S/C) AC machinery; and two use superconducting (S/C) DC machinery. Conventional electrical machines were eliminated because of their undesirable large sizes and heavy weights. In addition, configurations which would combine S/C-AC generators with S/C-DC motors were not considered in the current study.

A primary concern in the screening process was the compatibility requirement. For example, a high-speed destroyer with maximum installed power of 160,000-shp (119.4 MW) would require two units of the reference propulsion engine. This requirement implies that the transmission types with one input and two output shafts are not compatible with the two-thruster ships. Similarly those transmission systems having one input and one output shaft would not be compatible with the four-thruster ships. The same compatibility requirement can also be applied to the conventional destroyer.

The second concern in performing the screening is the component capability limitation projected for 1990. Table 2.1 presents projections of these limitations for major components needed in this study. It is recognized, however, that these projections depend on the research efforts, and therefore it was assumed that moderate research efforts would be continuously undertaken to provide these selected capacity limitations. Although the required auxiliary and control systems, (such as the cryogenic refrigeration system for the superconducting electric machinery, or the solid state control system, cycloconverter, rectifier and dynamic braking system, etc.) are not listed in Table 2.1, their availabilities are equally important. A last assumption, although less significant, was that any propulsion system requiring a hybrid transmission system (combining mechanical reduction gearbox with SEGMAG or superconducting electrical machinery) would not be considered. This consideration eliminates three potential alternative propulsion systems for the conventional destroyers as noted in the lower right corner of Fig. 2.4.

Based on the above requirements, twelve candidate propulsion system alternatives (designated as C1 to C12) were selected for further evaluation. Configurations C1 through C8 are the candidate propulsion systems for the high-speed destroyer ship type and configurations C9 to C12 are for conventional destroyer ships.

2.2 Critical Characteristics of Alternative Propulsion Systems

The overall propulsion system efficiency, size, specific weight, and specific capital cost for the twelve candidate propulsion system configurations are estimated in this section. The relative advantages and disadvantages of these configurations are discussed and tabulated. A later section will discuss the individual and overall relative ratings of these configurations.

The efficiency, size, weight, and capital cost characteristics of the reference (80,000-shp) closed-cycle gas turbine power conversion and fossil-fired heater systems have been discussed in Part I and Part II studies (Refs. 2.1 and 2.2). These results are directly applicable to the present study with the exception that the capital cost estimates must be escalated to 1979 dollar values. These escalation factors are based on either Nelson cost indexes (Ref. 2.3) or on an annual inflation rate of 7.5 percent for those items whose cost indices are not available.

The weight and volume estimates for the selected power conversion systems were based on information presented in Ref. 2.1 and 2.2 and in Phase III-1 of this report. The results are summarized in Tables 2.2 and 2.3. Estimates for the weight and volume of mechanical reduction gearboxes (epicyclic and offset types) were made using the methods described in Appendix D and Section 4 of the Part I report (Ref. 2.2). The shaft characteristics for the selected thrusters are based on the assumptions and equations of Ref. 2.2 and are summarized in Tables 2.4 and 2.5. In addition, the overall system weight and size can be significantly affected by auxiliary requirements. In particular, superconducting (S/C) transmission systems require cryogenic refrigeration and power conditioning subsystems, whereas mechanical gearboxes, shafts, and CRP propellers require lubrication and hydraulic subsystems and mechanical linkages.

The cryogenic refrigeration subsystem (CRS) usually consists of three major components; a compressor, a liquidifier, and liquid helium storage. The overall size, weight, and cost characteristics of the CRS depend on the propulsion system design philosophy. Generally, there are three options: (a) the CRS would be designed for continuous operation to provide the cooling requirements throughout the mission; (b) the CRS would be designed to maintain the S/C operation only, and the initial system cooldown would be achieved by transferring liquid helium from a base supply; and (c) a cryogenic reservoir of sufficient capacity would provide the initial cooldown and also sustain the S/C operation for the duration of the mission. In this study, a conservative estimate of the CRS characteristics was made based on the first option.

The estimated performance, overall size, weight, and cost characteristics for the cryogenic system requirements for various S/C generator and motor sizes are presented in Table 2.6. Based on studies by Greene (Ref. 2.5) and by

Mole (Ref. 2.6), it was found that the helium flow requirements for S/C AC and S/C DC generators are about the same. A comparison of the cooling requirements for the S/C motors from these two referenced studies (Greene studied an 18,000-shp S/C AC motor and Mole, a 40,000-shp S/C DC motor) also reaches the same conclusions. The helium flow requirements for the S/C AC or S/C DC machinery at different power ratings (20,000-shp, 40,000-shp, and 80,000-shp) were extrapolated from this data, and the results are presented in category A of Table 2.6. Based on the flow requirement for helium, the size, weight, and cost characteristics of the CRS suitable for integration with each S/C electrical transmission alternative was estimated; these are presented in category B of Table 2.6.

The size, weight, and cost characteristics of the cycloconverter, switchgear, dynamic braking system, power supply, and control systems were also estimated. Among these, the cycloconverter and switchgear are the most important components. Through a literature survey and personal consultation with experts from Otis Research and Development Center (Ref. 2.7) and from the Power Systems Division (Ref. 2.8) of United Technologies Corporation, it was found that together, these two components would measure approximately 2x3x3 meters, weigh 0.2 kg/kw, and cost $13.5/kw.

Tables 2.2 and 2.3 indicate that the use of advanced electrical (SEGMAG or superconducting) machinery may offer some savings in inboard shaft weight, but total elimination of inboard shaft is not realistic because of installation space requirements and vulnerability considerations. Table 2.3 shows that the advanced SEGMAG systems (C6 and C10) have the lowest specific volumes; these are followed in order by the superconducting DC system, the superconducting AC systems, and by the two mechanical systems; i.e., with the epicyclic and offset gearboxes. When the specific weights are compared (Table 2.2), the mechanical transmission using an epicyclic reduction gearbox is the lightest system; the S/C AC system is the second lightest; this is followed successively by the S/C DC systems, the SEGMAG systems, and the mechanical system with the offset gearbox.

The estimated efficiency and capital cost (in 1979 dollars) for the twelve selected configurations are presented in Tables 2.7 and 2.8, respectively. It should be noted that the efficiency and capital cost for advanced electrical machinery depend on many design parameters, including rotor speed, rated voltage and current, field excitation method, magnet winding, cooling method, applications, and market potential. It was found that a few estimates of efficiency were made in previous investigations for advanced electrical machinery; however, no cost information is available in the open literature for this machinery, and therefore original estimates were made. These projections are shown in Figs. 2.5 and 2.6, respectively.

The efficiency curves shown in Fig. 2.5 for advanced electrical machines were estimated by extrapolating data from the efficiencies of a few small

laboratory units and from the conceptual design results presented in Phase III-1. The efficiency curves of conventional electrical machinery were used as a guideline in this extrapolation process. The estimated specific prices of the superconducting (S/C) machinery are shown in Fig. 2.6. These specific price estimates were obtained from many sources; a personal consultation with an electrical machinery expert at UTRC (Ref. 2.4); an examination of the weight breakdown for the S/C machinery components; a comparison of the magnetic field winding and cooling methods; and a cost correlation between conventional DC and AC electrical machinery designs. Factors relating to their manufacturing tooling requirements were not considered. The specific price estimates presented in Fig. 2.6 therefore represent a component selling price whose R & D costs are assumed to be recovered under a separate contract.

Table 2.7 shows that there are no significant differences in overall propulsion efficiency at maximum output between the mechanical and electrical transmission systems. During part-load operation many tradeoffs are possible. The mechanical transmission must use its CRP thruster to try to equal the propulsion efficiency of the electrical system where the speeds of the gas generator and fixed-pitch propeller and are independent and can be set for highest overall efficiency. The most significant differences are expected at low power settings and when maneuvering where the flexibility of electrical cross-connection may be the predominant consideration. From the capital cost standpoint (Table 2.8), mechanical transmission systems are projected to be superior to those incorporating electrical transmissions. This conclusion can be traced to the need for those costly auxiliary equipments in the S/C electrical transmission systems.

2.3 Evaluation of Alternative Propulsion System Configurations

The criteria and methods for evaluating and selecting propulsion systems for the high-speed destroyer and the conventional destroyer are discussed in this section. The results of this evaluation indicate that there is no overwhelming preference between the two propulsion system configurations for future high-speed destroyers. These configurations integrate the same closed-cycle gas turbine propulsion engine with either an epicyclic reduction gearbox or the advanced segmented magnet (SEGMAG) DC machinery. For conventional destroyers, the most attractive configuration was found to be one which uses two SEGMAG DC generators and two SEGMAG-DC motors.

Prior to undertaking the evaluation and selection processes, a set of criteria was established as shown in Table 2.9. These evaluation criteria provide guidelines for evaluating the relative merits of the candidate propulsion system alternatives and include the critical criteria examined in the previous section, as well as other important, though more subjective criteria. Table 2.10 presents the results of using these criteria to select the preferred lightweight propulsion systems for the two reference ship types.

The selection of preferred propulsion system configurations for both high-speed and conventional destroyers, as shown in Table 2.10, consists of three parts: a set of evaluation criteria; a set of weighting factors; and a set of individual ratings. The evaluation criteria shown in Table 2.9 include factors to rate technical characteristics such as the system weight, volume (compactness), and performance (fuel efficiency) characteristics. These are followed successively by assessments of each configuration's reliability/maintainability, interface with the ship (such as the impact on ship layout and design), auxiliary equipment requirements, system controllability and dynamic response characteristics, and economic characteristics (which include the capital cost characteristics and the research and development requirements). Personnel from ONR have been consulted to establish these evaluation parameters and the weighting given to each factor. The weighting factors reach a maximum of 5 to represent the relative importance of each evaluation criterion in the overall system evaluation. The individual ratings for each configuration was quantitatively established (where possible) and given a number from 1 to 5. It should be noted that the configurations which apply to the high-speed destroyer were made independently of the ratings for the conventional destroyer.

The individual ratings for each configuration in terms of system weight, volume (compactness), and the projected capital cost are based upon values identified in Tables 2.2 through 2.8 and are summarized in lines 1, 2, and 9 of Table 2.10. It should be noted that the ratings given for the "compactness" criteria did not rely entirely upon the volume estimates presented in Table 2.3. Also considered were the interstitial volume requirements for service between components. For example, a configuration which requires several motors and generators may require more total engine room volume (after allowing for maintenance and service) than a mechanical gearbox which is totally enclosed in one package, even though the latter may enclose more volume than the summation of the electrical components.

The rating of the system "fuel efficiency" (line 3 of Table 2.10) was based on the fuel consumption rates presented in Tables 1.8 and 1.9 and efficiencies presented in Table 2.7. The S/C electrical transmission systems (superconducting and advanced SEGMAG machinery) are rated 5 in comparison to a rating of 4 for mechanical transmissions since overall fuel usage is slightly lower for the S/C electrical configurations when operating at either cruise speed for 3000 nautical miles, or in accordance with the duty cycle.

To rate system Reliability and Maintainability (line 4, Table 2.10), the status of component technologies and system complexities were considered. Since there has been no significant operational experience with any SEGMAG or superconducting electrical machinery, maintainability, and reliability data are lacking. One thing believed certain is that the added complexity required for cooling the superconducting windings would shorten the operating time between failure (TBF). Only experience will provide an answer to the question of

whether the superconducting machinery can achieve the high reliability inherent with conventional electric machinery. On the other hand, mechanical reduction gearboxes and associated shafting have been proven to be very reliable components. Statistics show that the TBF for mechanical reduction gears is as high as 7 x 10^5 hrs and those for the shafting (including bearings) and thruster are approximately 5 x 10^5 and 16 x 10^6 hours (Ref. 2.1), respectively. Therefore, the ratings shown in Table 2.10 follow naturally.

Based on the component size characteristics presented in Table 2.3, preliminary propulsion system layouts for each configuration were prepared to identify potential installation problems aboard the ships. These layout drawings are shown in Figs. 2.7 through 2.9. It should be noted that in preparing these propulsion system layouts, consideration was given to the ship vulnerability and to the lower weight of inboard shafting in comparison to outboard shafting. Subsequently, the flexibility of arranging the propulsion system components, the integration problems with the ship, and the impact on the ship layout design were used to obtain the ratings for "ship layout" for each of the alternative configurations shown on line number 5 of Table 2.10.

Line 6 of Table 2.10, "auxiliary requirements", presents the ratings related to the requirements of each configuration for auxiliaries such as control, cooling, and power conditioning. Control of conventional propulsion systems using mechanical transmissions integrated with steam engines, open-cycle gas turbine engines, or diesel engines, does not require excessively large or complex auxiliaries. For control of electrical transmission systems, many of the same components would be required plus several other auxiliary devices. These auxiliary devices include components such as the solid state control system, cycloconverter, rectifier, and dynamic braking systems. For superconducting electric machinery systems, auxiliaries are also required for cryogenic refrigeration system and its accessory control devices to regulate the helium flow and maintain the machinery at cryogenic conditions for any level of operation. In addition, since the superconducting field winding must be in an environment of 4.2K, requirements for cooling from room temperature must also be considered. For example, as noted previously for the superconducting AC machines considered by Greene (Ref. 2.5), a period of up to 20 hours may be required to cool the machine from room temperature to 4.2K. To avoid this long cool-down time, Greene suggested that the superconducting winding be kept at or near cryogenic temperature when the propulsion system is on standby thus increasing auxiliary requirements for fuel and manpower. Consequently, mechanical transmission systems, the SEGMAG systems, the superconducting DC systems, and the superconducting AC systems are rated 5, 4, 3, and 2, respectively.

The rating of system controllability and dynamic response characteristics for each candidate propulsion system is shown on line 7 of Table 2.10. Because the electric machinery systems can provide a more desirable match between prime mover and thrustor, and because they can be easily integrated with future automated and computerized control systems (by controlling the voltage and

excitation field to provide quick response to the load change), these systems were considered for a higher rating than the mechanical system. However, the response time of a superconducting system is limited by the heat transfer characteristics between the helium flow and the superconducting winding. In particular, the cool-down period required upon startup could be a significant problem in an emergency situation such as that happened at Pearl Harbor in 1941. When taking these factors into consideration, the SEGMAG systems (C2, C6, and C10) are rated highest (5), and the rest of the systems are rated 4, except for Configuration C9. Configuration C9 uses one off-set gearbox to drive two shafts and would experience significant disadvantages in terms of manueverability and therefore, C9 is given a rating of 3.

The evaluation criterion entitled "Operational Flexibility" was used to account for the ability of each propulsion system configuration to meet maneuverability or unusual mission demands, or to overcome damaged components. For example, if one thrustor on a high-speed destroyer were inoperative, the configurations which normally have four thrustors available (C5 through C8) would be capable of providing more thrust than a configuration which normally operates on only two thrustors. The four-thrustor configuration would also allow better directional control and maneuverability when operating on four or three units as compared to a two-thrustor ship operating on two or one unit. Furthermore, ships which use electric transmission systems allow more flexibility of operation than configurations which use mechanical transmissions. The electric transmission systems can allow power from both gas turbines to be distributed to the thrustors in a more flexible manner. For example, full power could be supplied to the remaining thrustors if some were damaged, as in the example just cited. More importantly, the electric transmissions can also allow one gas turbine to drive all of the operational thrustors if the other gas turbine is inoperative, or inefficient to operate. This "cross-connection" is not possible in a mechanical transmission system without excessive gearing and shafting requirements. (Cross-connection can also be used to improve the fuel economy at low power levels, but this characteristic was considered in another criterion.) Thus, the ratings presented in Table 2.10 give the four-shaft ships with electric propulsion the highest marks among all the high-speed destroyer configurations considered.

The logic for the ratings in "Operational Flexibility" for conventional destroyer configurations follows the same course. Electric transmissions are rated high while the mechanical gearbox configuration is rated low. The latter rating is particularly low for the conventional destroyer since only a single gas turbine is used to drive two propeller shafts. It would be difficult to operate one thrustor if the other one was damaged, and maneuvering would place a heavy dependence on CRP propellers because the speed of the two shafts would be dependent on each other.

To rate the system "Development Requirement" (see line 10, Fig. 2.10) the state-of-the-art technologies of each propulsion system component, any inherent design problem(s), and capacity limitations were considered. For example,

the development of SEGMAG machinery is still in its early stages, and only one conceptual design each has been made for a generator (20,000 shp), and for a motor (40,000 shp). Laboratory tests have yet to be conducted on this concept. In contrast, many studies, including testing, have been made on superconducting machinery in the past decade. Laboratory tests have been conducted at power levels over 2000 kW and conceptual designs have been produced for units with ratings as high as 2,000 MW. The latter, large sizes, were designed for A/C, land-based applications, as has been true for most S/C AC work. S/C DC studies have often been targeted for ship-propulsion applications and are therefore expected to need less development requirements than S/C AC systems. Therefore, proper credits were given to these past efforts in rating the development requirements for superconducting electric propulsion systems.

In the mechanical transmission systems, the configurations presented as C-1 and C-9 are beyond the current state-of-the-art and therefore are given a rating of 4 instead of 5. Relative to these development requirements, the electrical systems were rated 3 and 2. The SEGMAG concept is given an equal rating with S/C-DC because SEGMAG would incorporate new geometric design and fabrication concepts as opposed to the unfamiliar environment in which S/C-DC materials must operate.

Based on the weighting factors and the indivudal ratings for each propulsion system configuration identified, the total rating for each configuration was calculated by summing the products of the weighting factor and their corresponding ratings for all criteria of each system. The results are shown on the bottom line of Table 2.10. It was found that configurations C1 (a configuration using epicyclic gearbox) and C2 (a configuration using a SEGMAG transmission system) are almost equally attractive propulsion systems for the reference high-speed destroyer ships. The difference between the final ratings of these two preferred systems results primarily from the combined effects of differences in ratings for system weight, reliability, auxiliary requirements, capital cost, and component development requirements. In order to promote the advanced SEGMAG-DC propulsion system to a dominant position relative to the epicyclic reduction gearbox system, significant research efforts must be carried out to improve some of these characteristics and demonstrate other attractive characteristics.

For the conventional destroyer, intended for use in the 1990's, the results of the rating indicate that the advanced SEGMAG-DC system, configuration C10, is more desirable than the other alternative systems. It should be mentioned that all the conventional destroyer configuration ratings are very close to each other. A close examination of individual ratings for the configurations C9 through C12 on Table 2.10 would reveal that the advanced SEGMAG and superconducting electrical transmission systems could offer greater potential for naval ship propulsion applications, than the mechanical transmission system provided that current research and development efforts continue, and that these efforts lead to a demonstration of good compactness, fuel efficiency, control, and operational flexibility; and that potential limitations in reliability, auxiliary requirements, capital costs, and development are insignificant.

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(PHASE III-2)

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TABLE 2.1

ALTERNATIVE LIGHTWEIGHT PROPULSION SYSTEM
COMPONENT CAPABILITY LIMITATIONS
(Projected 1990 Technologies)

Component	Maximum Unit Capacity (shp)	No. Units	Configuration
Propulsion Engine*	80,000	<2	Fossil-fired CCGT
Gearbox			
Offset	<150,000	<2	1 or 2 stages
Epicyclic	<100,000	<2	1 or 2 stages
Electric Generator & Motor			
Superconducting AC	$<5 \times 10^6$	<4	Synchronous or
Superconducting DC	<100,000	<4	Induction Type
SEGMAG	<60,000**	<4	
Thruster			
Fixed Pitch	<100,000	<4	Sub and Super
C.R.P.	<60,000	<4	Cavitating

*Based on conceptual design results performed in Phase II of this Study Program (Ref. 1).

**Personal conversation with Mr. K. Ellingsworth of ONR and also with Westinghouse personnel involved in the SEGMAG Program.

TABLE 2.2

ALTERNATIVE PROPULSION SYSTEM WEIGHT* CHARACTERISTICS
(All data are in kg/kW)

Alternative** Propulsion System Configuration	Heater* System	Power* Conversion System	Transmission System						Thruster	Overall Propulsion System
			Mechanical	Electrical			Shafting			
				Generator	Motor	Auxiliary Subsystems	Inboard	Outboard		
C1	1.915	1.301	.529	---	---	---	.249	.292	.055	4.341
C2			---	.474	.486	.456	.073	.249	.055	5.010
C3			---	.188	.426	.274	.073	.249	.055	4.481
C4			---	.426	.535	.091	.073	.249	.055	4.645
C5			2.244	---	---	---	.231	.176	.097	5.964
C6			---	.474	.486	.456	.079	.170	.055	4.937
C7			---	.188	.353	.274	.079	.170	.055	4.335
C8			---	.426	.444	.091	.079	.170	.055	4.481
C9			2.244	---	---	---	.669	.736	.936	7.801
C10			---	.474	1.429	.456	.389	.736	.511	7.211
C11			---	.188	1.003	.274	.389	.736	.511	6.317
C12			---	.426	1.277	.091	.389	.736	.511	6.645

*The weight estimates do not include bed plate.

**Configurations C1 to C8 are for the High-Speed Destroyer and C9 to C12 are for the Conventional Destroyer and the ratings for the two ship types are made independently of each other.

TABLE 2.3

ALTERNATIVE PROPULSION SYSTEM SIZE CHARACTERISTICS
(All the dimensions are in meters)

Propulsion System Configuration	Heater System (WxLxH)	Power Conversion System (WxLxH)	Transmission System: Mechanical (DxL)	Electrical: Generator (DxL)	Electrical: Motor (DxL)	Electrical: Auxiliary Subsystems (WxLxH)	Shafting, DxL: Inboard	Shafting, DxL: Outboard	Thruster DxL	Overall System Volume (m^3)
C1	6x6.6x5.3	5.3x12.8x4	4x4.3	-	-	-	47	42	3.1x0.6	562
C2			-	1.07x2.35 (2 units)	2.16x1.52 (2 units)	1x2.5x5	14	36	3.1x0.6	527
C3			-	1.28x2.80	1.95x2.16	(2x3x3)+ (1x2.5x5)+ (2.3x4.1x2.3)	14	36	3.1x0.6	562
C4			-	1.58x1.92	2.04x3.26	(1x2.5x5)+ (2.3x4.1x2.3)	14	36	3.1x0.6	548
C5			3.2x10.2x5.0	-	-	-	100	58	2.5x0.5	666
C6			-	1.07x2.35 (2 units)	2.16x1.52 (2 units)	1x2.5x5	34	54	2.5x0.5	522
C7			-	1.28x2.80	1.58x1.43 (2 units)	(2x3x3)+ (1x2.5x5)+ (2.4x4.6x2.4)	34	54	2.5x0.5	560
C8			-	1.52x1.83	1.55x2.50 (2 units)	(1x2.5x5)+ (2.4x4.6x2.4)	34	54	2.5x0.5	546
C9			3.2x10.2x5.0	-	-	-	48	40	5.2x1.0	692
C10			-	1.07x2.35 (2 units)	2.16x1.52 (2 units)	1x2.5x5	28	40	5.2x1.0	551
C11			-	1.28x2.80	2.26x2.04 (2 units)	(2x3x3)+ (1x2.5x5)+ (2.4x4.6x2.4)	28	40	5.2x1.0	601
C12			-	1.58x1.92	2.16x3.44 (2 units)	(1x2.5x5)+ (2.4x4.6x2.4)	28	40	5.2x1.0	592

TABLE 2.4

SHAFT CHARACTERISTICS FOR SELECTED SHIP TYPES

A. Weight Characteristics for Hollow Shaft @ Ratio of Inner/Outer Dia = .65:
(W = Weight in Kg, L = Length in m)
For High Speed Destroyer:

$$W(\text{Inboard}) = 2.18\ L\ (\text{SHP/RPM})^{2/3}$$

$$W(\text{Outboard}) = 2.89\ L\ (\text{SHP/RPM})^{2/3}$$

For Conventional Destroyer

$$W(\text{Inboard}) = 2.46\ L\ (\text{SHP/RPM})^{2/3}$$

$$W(\text{Outboard}) = 3.27\ L\ (\text{SHP/RPM})^{2/3}$$

B. Cost Characteristics for Hollow Shaft @ Ratio of Inner/Outer Dia = .65:
(C = Capital cost in 1979 dollars)
For High Speed Destroyer

$$C = 7.2 \times \left[W(\text{inboard}) + W(\text{outboard})\right]$$

For Conventional Destroyer

$$C = 5.0 \times \left[W(\text{inboard}) + W(\text{outboard})\right]$$

TABLE 2.5

CHARACTERISTICS OF SELECTED THRUSTERS

Thruster Power 1000 shp (MW)	Ship Max. Speed (km/hr)	Thruster Type	Max. RPM	Efficiency (%)	Diameter (m)	Specific Weight* (kg/kW)	Specific Cost* ($/kW)
20 (14.9)	5.0	F.P. Subcav.	320	75	4.0	.74	5.59
	5.0	F.P. Subcav.	230	75	5.2	.82	6.26
40 (29.8)	5.0	C.R.P. Subcav.	230	75	5.2	.94	14.21
	7.2	C.R.P. Supercav.	980	65	2.5	.06	1.91
80 (59.7)	7.2	F.P. Supercav.	580	65	3.1	.05	0.77

*Dry Weight = $f_w D^3$ and Estimated Cost = $f_c D^3$

Where D = diameter in meters, weight in kg, cost in 1979 dollars

f_w = 100 or f_c = 1550 for F.P. Supercavitating, Titanium
f_w = 120 f_c = 3650 for C.R.P. Supercavitating, Titanium
f_w = 175 f_c = 1300 for F.P. Subcavitating, Ni AlB_r
f_w = 200 f_c = 3010 for C.R.P. Subcavitating, Ni AlB_r

TABLE 2.6

PRELIMINARY ESTIMATES OF CRYOGENIC REFRIGERATION SYSTEM
CHARACTERISTICS FOR ALTERNATIVE SUPERCONDUCTING ELECTRIC PROPULSION SYSTEMS.

A. Estimated Helium Flow Requirement (Equivalent Liter/Hr)

Unit Power Rating (shp)	AC or DC Generator	AC or DC Motor
20,000	6.75	10.5
40,000	8.50	15.5
80,000	11.00	22.0

B. Estimated Cryogenic Refrigeration System Characteristics, (Cost is in 1979 Dollars)

Configuration	Helium Flow (Equiv. 1/hr)	System Size (LxWxH,m)	System Weight (Kg)	Input Power (KW)	Cost (1979 Value) (1000$)
1. One 80,000-Shp Gen. One 80,000-Shp Motor	33.0	2.3 x 4.1 x 2.3	2800	69	350
2. One 80,000-Shp Gen. Two 40,000-Shp Motor	42.0	2.4 x 4.6 x 2.4	3200	88	410
3. One 80,000-Shp Gen. Four 20,000-Shp Motor	53.0	2.7 x 4.6 x 2.7	3500	110	680

TABLE 2.7

ALTERNATIVE PROPULSION SYSTEM EFFICIENCY CHARACTERISTICS

• at maximum output

Propulsion** System Configuration	Heater System	Power Conversion System	Transmission System: Mechanical	Transmission System: Electrical Generator	Transmission System: Electrical Motor	Transmission System: Electrical Cryogenic* System	Thruster	Overall Propulsion Efficiency (%)
C1	.875	.404	.95	-	-	-	.65	21.83
C2	↓	↓	-	.988	.979	-	.65	22.25
C3	↓	↓	-	.995	.98	.9988	.65	22.49
C4	↓	↓	-	.995	.98	.9988	.65	22.49
C5	↓	↓	.98	-	-	-	.65	22.52
C6	↓	↓	-	.988	.979	-	.65	22.23
C7	↓	↓	-	.995	.982	.9985	.65	22.42
C8	↓	↓	-	.995	.982	.9985	.65	22.42
C9	↓	↓	.98	-	-	-	.75	25.98
C10	↓	↓	-	.988	.979	.9985	.75	25.61
C11	↓	↓	-	.995	.982	.9985	.75	25.87
C12	↓	↓	-	.995	.982	.9985	.75	25.87

*$\eta = 1 - $ (Cryogenic Compressor Power Input ÷ 80,000 Shp)

** Configurations C1 to C8 are for the High-Speed Destroyer and C9 to C12 are for the Conventional Destroyer

The ratings for the two ship types are made independent of each other.

TABLE 2.8

ALTERNATIVE PROPULSION SYSTEM COMPONENT COST CHARACTERISTICS
(All cost data are in $/kw and 1979 dollars)

Alternative Propulsion System Configuration	Heater System	Power Conversion System	Transmission System						
				Electrical					
			Mechanical	Generator	Motor	Auxiliary Subsystems	Shafting	Thruster	Overall Propulsion System
C1	227.7	166.7	17.3	---	---	---	8.6	0.77	421
C2			---	26.0	35.0	18.1	5.1	0.77	474
C3			---	7.9	12.6	71.7	5.1	0.77	474
C4			---	17.7	28.2	18.1	5.1	0.77	465
C5			45.8	---	---	---	6.4	3.00	450
C6			---	26.0	35.0	18.1	4.0	0.91	472
C7			---	7.9	13.1	71.7	4.0	0.91	474
C8			---	17.7	29.0	18.1	4.0	0.91	466
C9			45.8	---	---	---	15.5	21.36	477
C10			---	26.0	102.8	18.1	12.5	3.70	552
C11			---	7.9	37.4	71.7	12.5	3.70	510
C12			---	17.7	83.3	18.1	12.5	3.70	532

Table 2.9

ALTERNATIVE PROPULSION SYSTEMS EVALUATION CRITERIA

1. Lightweight
2. Compactness
3. Fuel Efficiency
4. Ship Layout
5. Auxiliary Requirement
6. Control and Response
7. Operational Flexibility
8. Reliability and Maintainability
9. Projected Capital Cost
10. Development Requirement

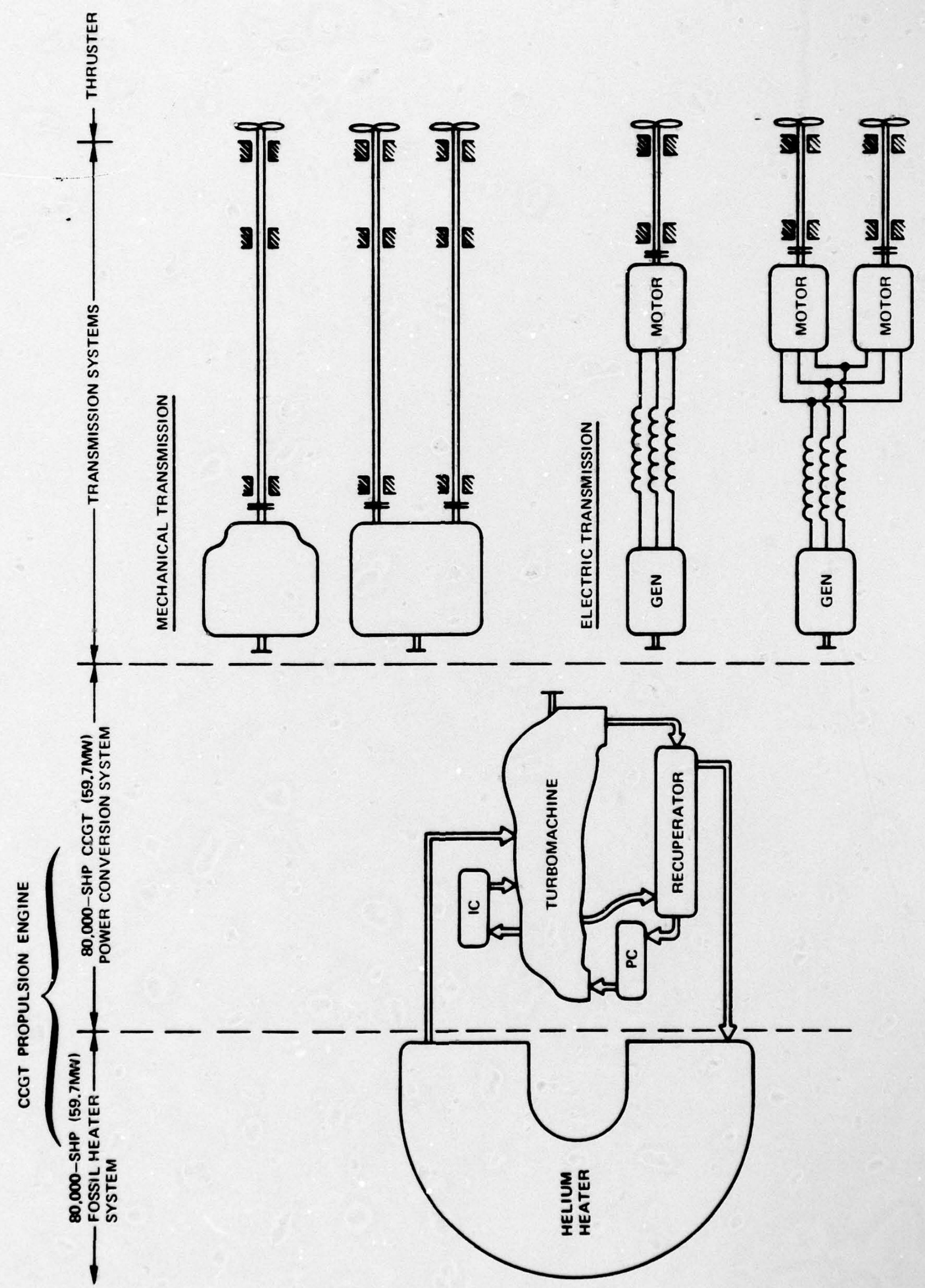
Table 2.10

SELECTION OF REFERENCE LIGHTWEIGHT PROPULSION SYSTEMS

Evaluating Criteria	Weighting Factor 1 to 5	Rating of Alternative Propulsion System Configurations											
		High-Speed Destroyers								Conventional Destroyers			
		2-Engines, 2-Shafts				2-Engines, 4-Shafts				1-Engine, 2-Shafts			
		C1 EPIC	C2 SEG MAG	C3 S/C AC	C4 S/C DC	C5 OFF SET	C6 SEG MAG	C7 S/C AC	C8 S/C DC	C9 OFF SET	C10 SEG MAG	C11 S/C AC	C12 S/C DC
1. Lightweight	5	5	4	5	5	3	4	5	5	3	4	5	5
2. Compactness	5	5	5	4	4	3	4	3	3	4	5	4	4
3. Fuel Efficiency	5	4	5	5	5	4	5	5	5	4	5	5	5
4. Reliability & Maintainability	5	5	4	3	3	5	4	3	3	5	4	3	3
5. Ship Layout	4	4	5	5	5	2	3	3	3	4	5	5	5
6. Auxiliary Requirement	4	5	4	2	3	5	4	2	3	5	4	2	3
7. Control & Response	4	4	5	4	4	4	5	4	4	3	5	4	4
8. Operational Flexibility	3	3	4	4	4	4	5	5	5	2	5	5	5
9. Projected Capital Cost	3	5	4	4	4	5	4	4	4	5	3	4	4
10. Development Requirement	2	4	3	2	3	4	3	2	3	4	3	2	3
TOTAL RATING		179	176	157	163	151	166	147	153	157	176	160	166

FIG. 2.1

ALTERNATIVE PROPULSION SYSTEM SCHEMATIC



79–05–83–1

FIG. 2.2

PROPULSION SYSTEM LAYOUT FOR HIGH SPEED DESTROYER

- 3556 METRIC TONS (3,500 LONG TONS)
- EPICYCLIC GEARBOX CONFIGURATION
- 119.4MW (160,000 SHP)

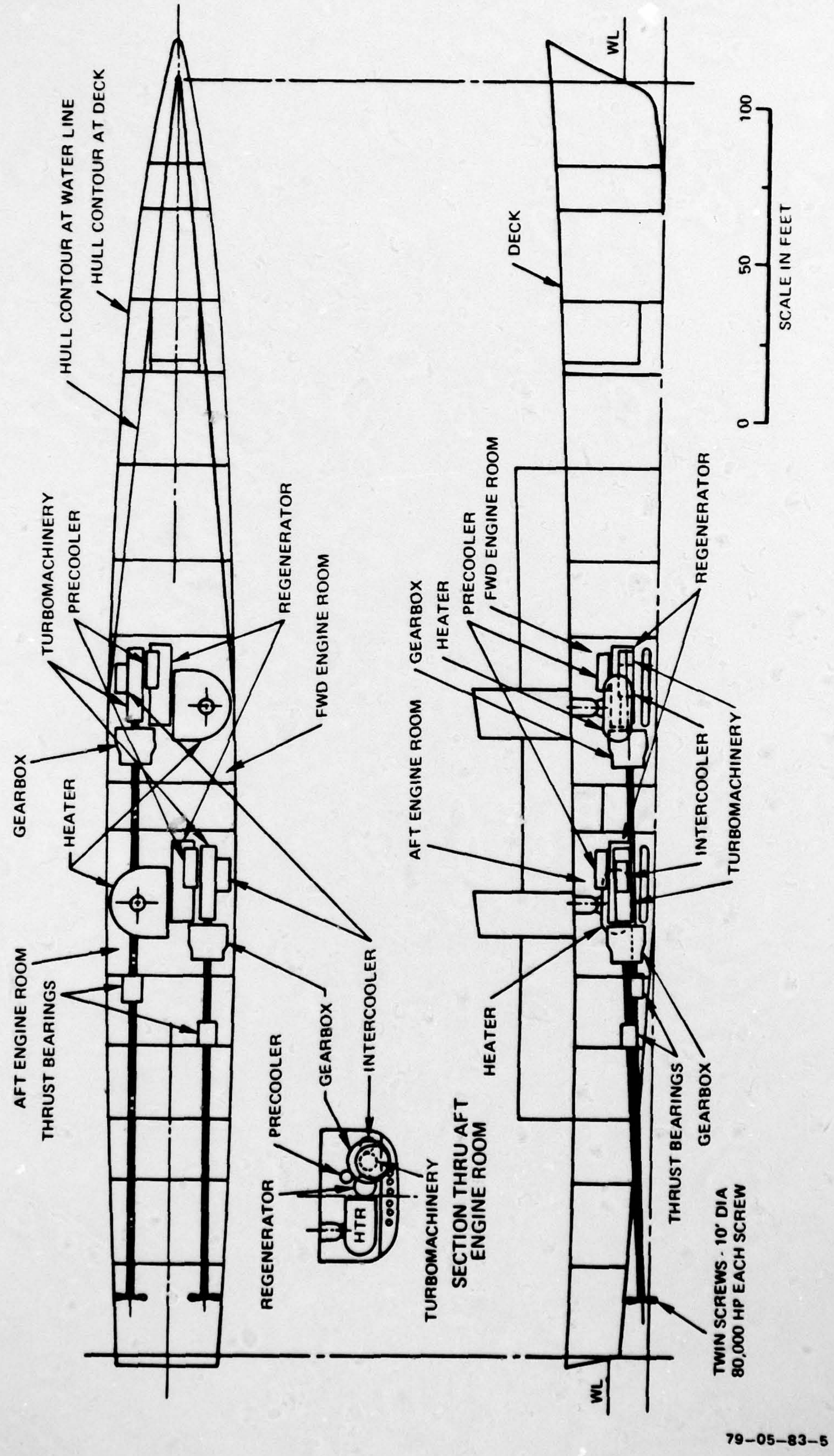


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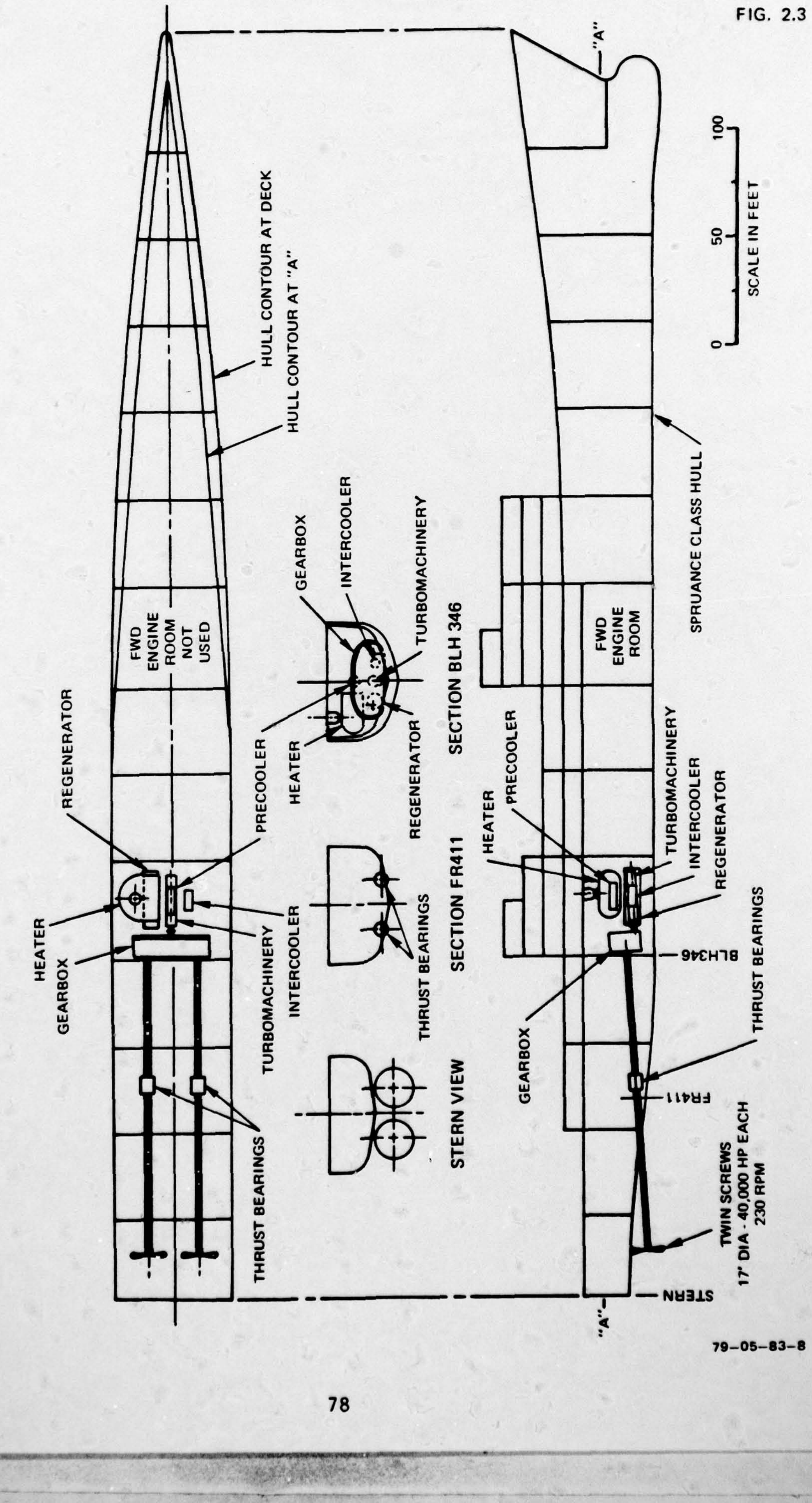
FIG. 2.3

PROPULSION SYSTEM LAYOUT FOR CONVENTIONAL DESTROYER

- 7925 METRIC TONS (7,800 LONG TONS)
- OFFSET GEARBOX
- 59.7MW (80,000 SHP)
- DD 963 SIZE



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SELECTION MATRIX FOR ALTERNATIVE TRANSMISSION SYSTEMS

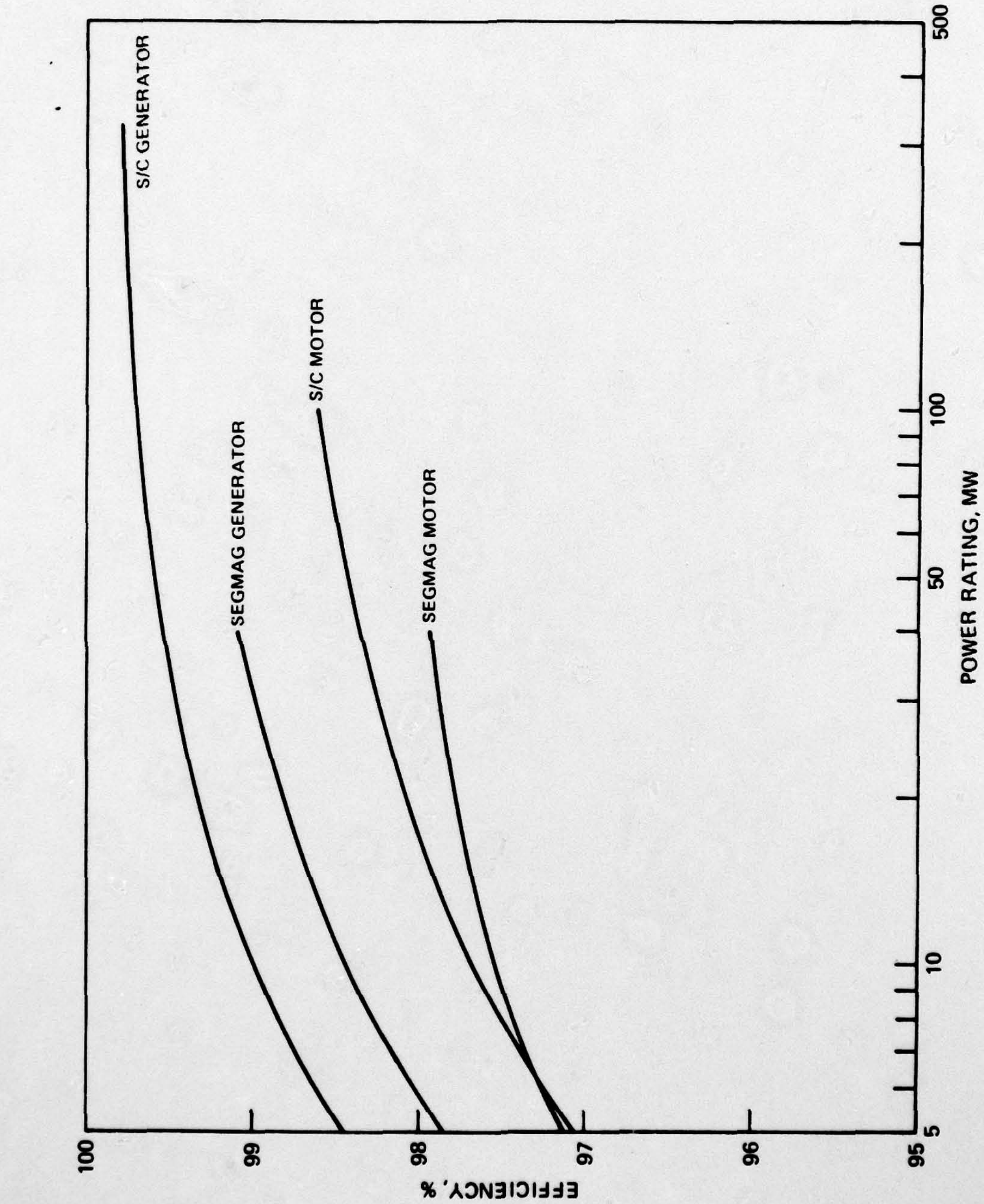
PRIME MOVER = 59.7MW (80,000 SHP) FOSSIL-FIRED CLOSED-CYCLE HELIUM GAS TURBINE ENGINE (REF. 2.1)

INCOMPATIBLE — COMPONENT CAPACITY LIMITATION — NEED BOTH MECH. & ELEC. TRANSMISSIONS (HYBRID)

TRANSMISSION TYPE	HIGH SPEED DESTROYER INSTALLED POWER 160,000 SHP			CONVENTIONAL DESTROYER INSTALLED POWER 80,000 SHP		
DESCRIPTION	PROPULSION SYSTEM	2 THRUSTORS	4 THRUSTORS	PROPULSION SYSTEM	2 THRUSTORS	4 THRUSTORS
EPYCYCLIC GEARBOX	2 UNITS	C1		1 UNIT		
OFFSET GEARBOX	2		C5	1	C9	
SEGMAG GENERATOR; SEGMAG GENERATOR; CONTROL; SEGMAG MOTOR; SEGMAG MOTOR	2	C2		1		
S/C AC GENERATOR; CONTROL, CYCLOCONV. BRAKING; CRYOGENIC SYS.; S/C AC MOTOR	2	C3		1		
S/C DC GENERATOR; CONTROL BRAKING; CRYOGENIC SYS; S/C DC MOTOR	2	C4		1		
SEGMAG GENERATOR; SEGMAG GENERATOR; CONTROL; SEGMAG MOTOR; SEGMAG MOTOR	2		C6	1	C10	
S/C AC GENERATOR; CONTROL RECTIFIER CYCLOCONV. BRAKING; CRYOGENIC SYS.; S/C AC MOTOR; S/C AC MOTOR	2		C7	1	C11	
S/C DC GENERATOR; CONTROL BRAKING; CRYOGENIC SYS.; S/C DC MOTOR; S/C DC MOTOR	2		C8	1	C12	

79-05-83-2

PROJECTED SUPERCONDUCTING AND SEGMAG MACHINERY EFFICIENCY



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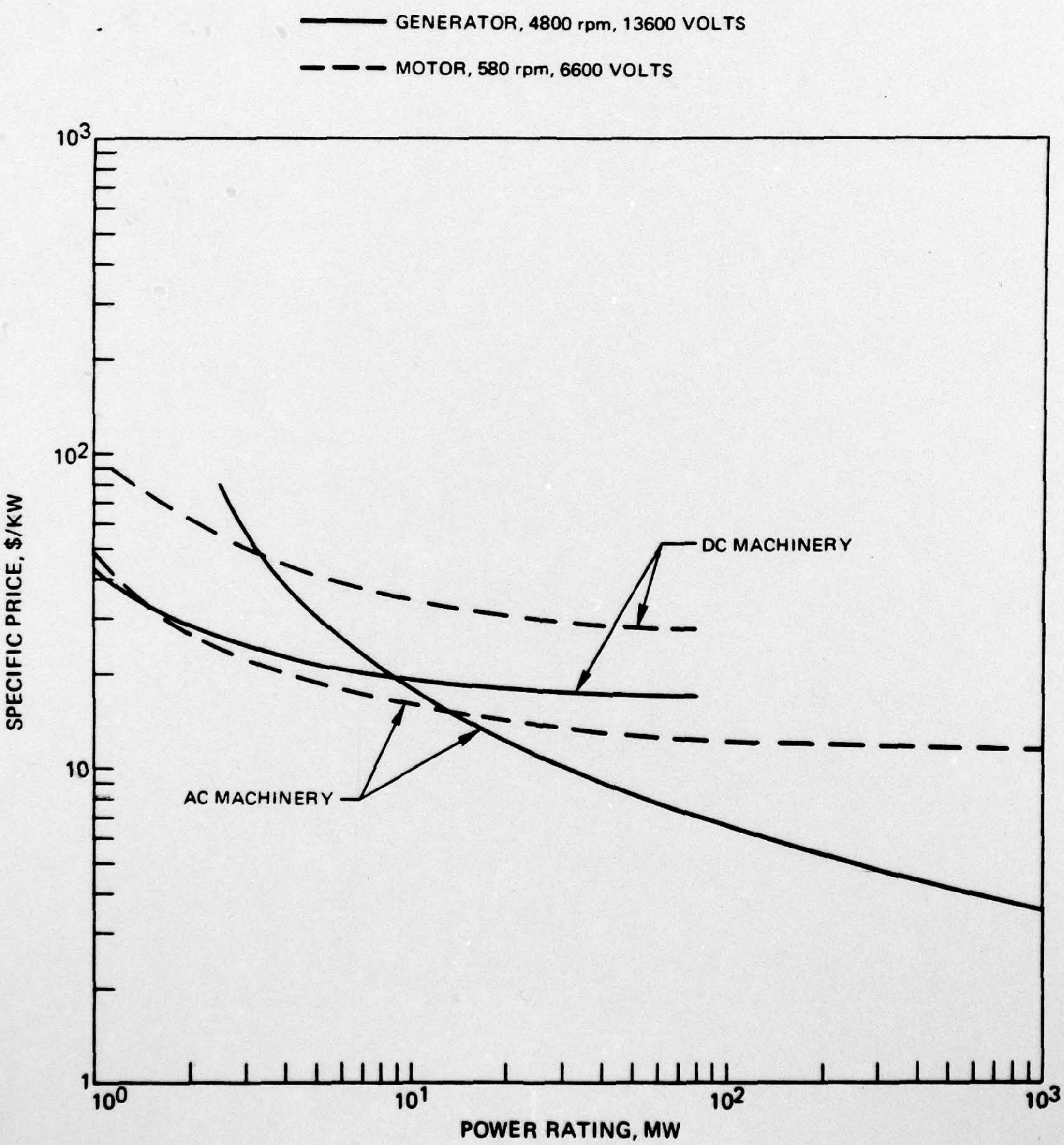
ESTIMATED SUPERCONDUCTING MACHINERY SPECIFIC PRICE (1979 DOLLARS)



79–05–83–4

FIG. 2.7

ALTERNATIVE PROPULSION SYSTEM CONFIGURATION LAYOUTS FOR HIGH SPEED DESTROYERS

• 2 SHAFTS AND THRUSTERS

H = HEATER, B = BEARING, G = GEARBOX OR GENERATOR, P = PRECOOLER, I = INTERCOOLER,
T = TURBOMACHINERY, RG = REGENERATOR, M = MOTOR, RF = REFRIDGERATION SYSTEM

CONFIGURATION CODE

SHIP LAYOUT

C1 (EPICYCLIC GEARBOX)

C2 (SEGMAG MACHINERY)

C3 (SUPERCONDUCTING AC MACHINERY)

C4 (SUPERCONDUCTING DC MACHINERY)

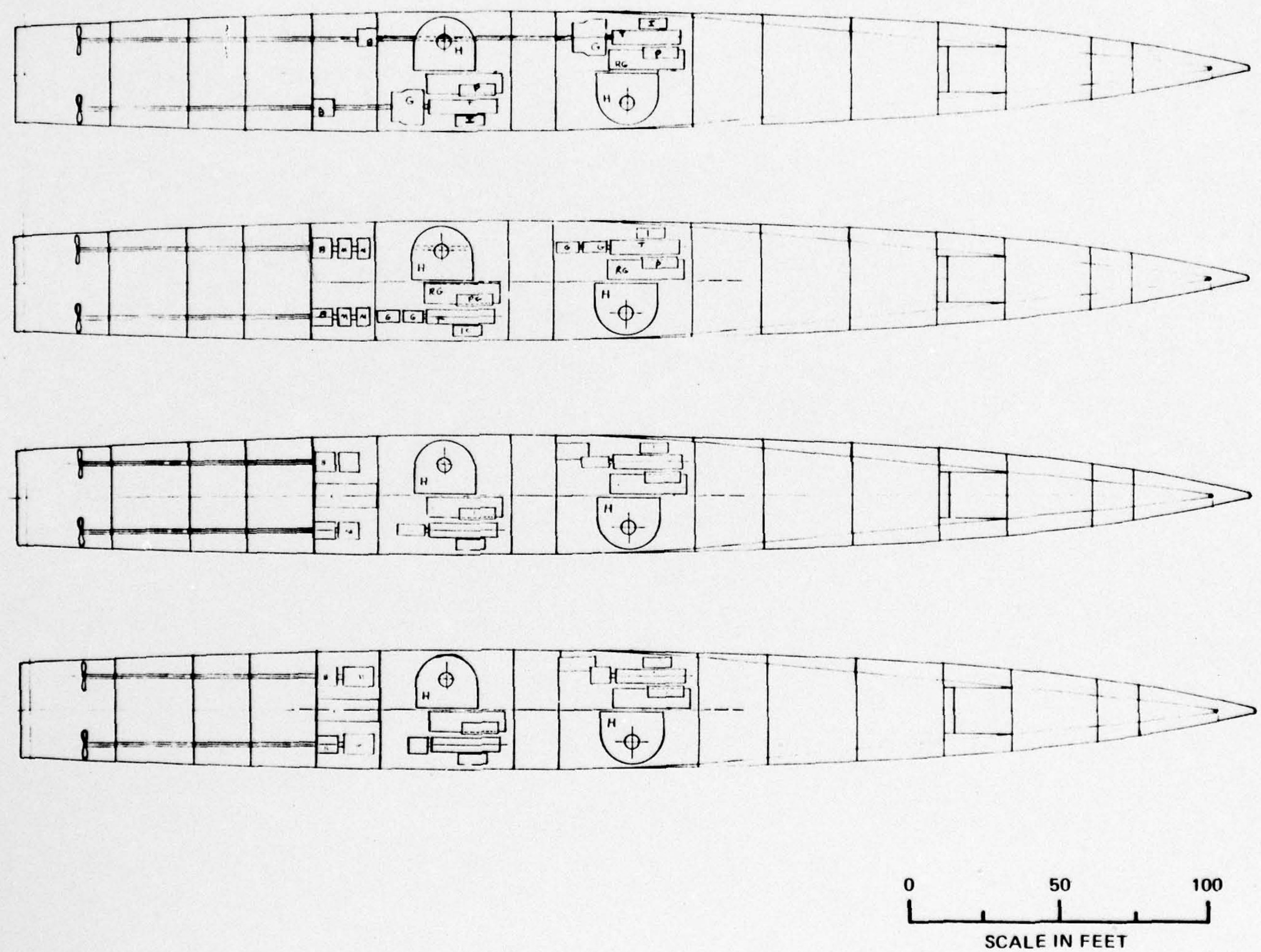


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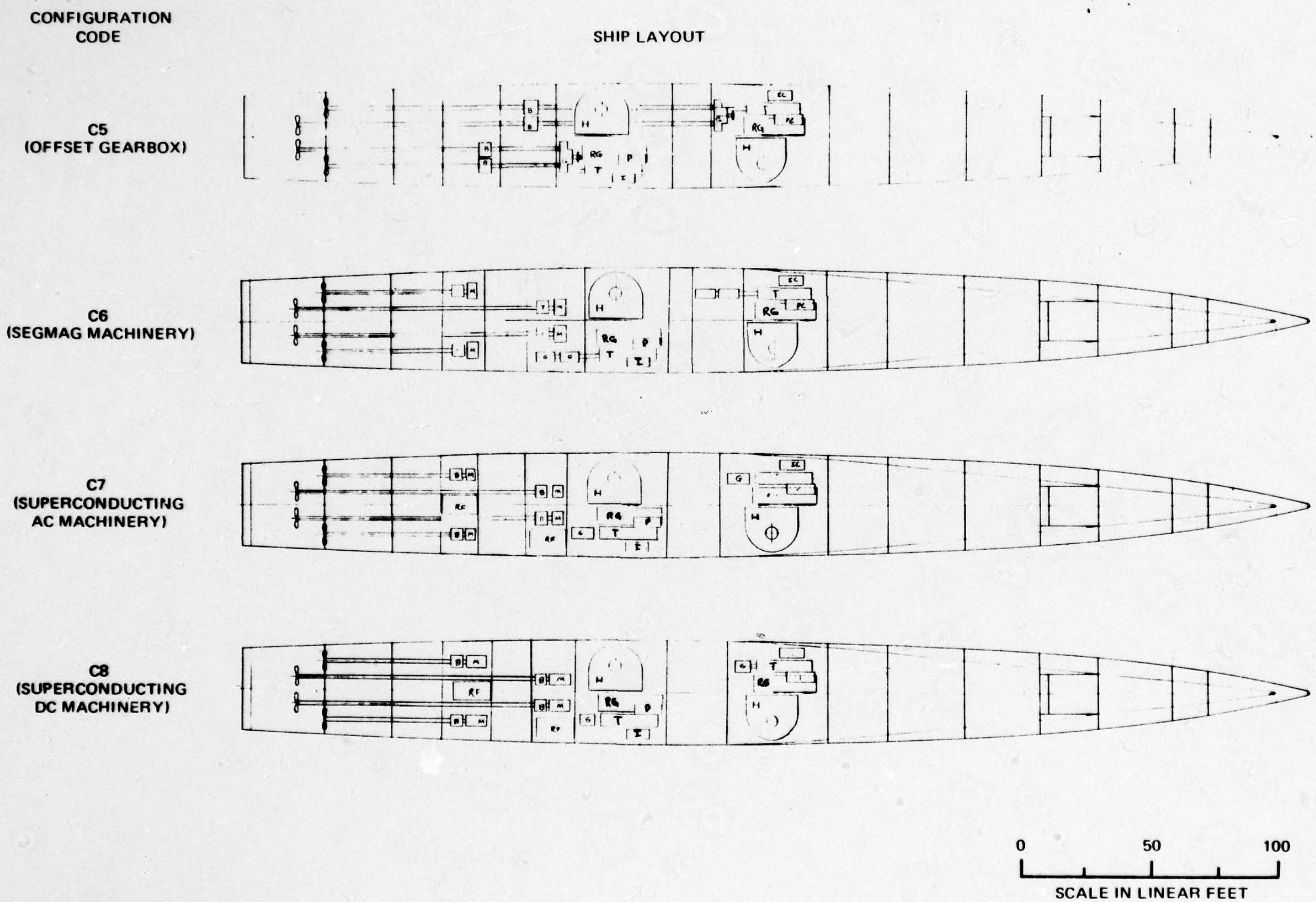
FIG 2.8

ALTERNATIVE PROPULSION SYSTEM CONFIGURATION LAYOUTS FOR HIGH SPEED DESTROYERS

- 4 SHAFTS AND THRUSTERS

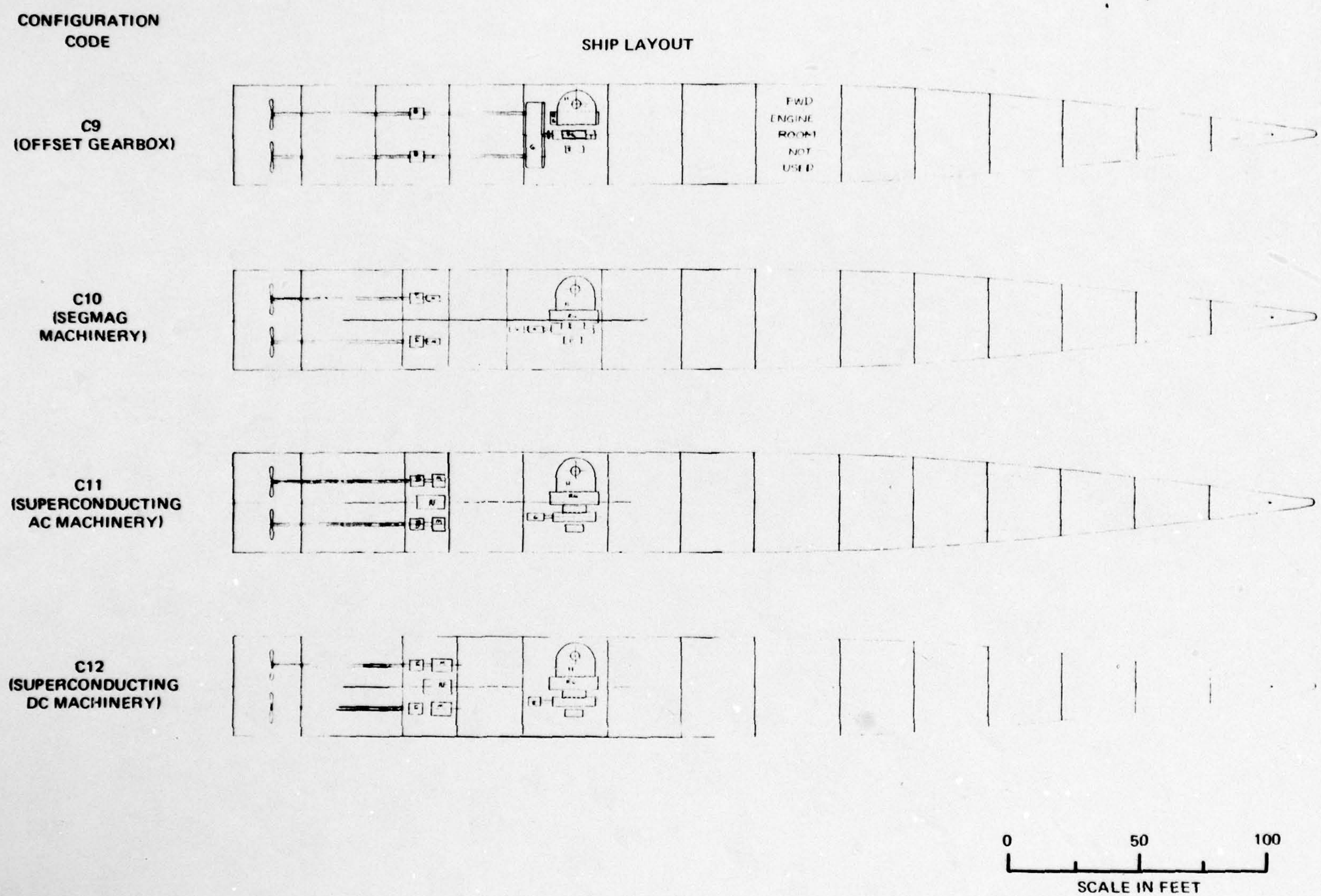
H = HEATER, B = BEARING, G = GEARBOX OR GENERATOR, P = PRECOOLER, I = INTERCOOLER,
T = TURBOMACHINERY, RG = REGENERATOR, M = MOTOR, RF = REFRIDGERATION SYSTEM



79–05–83–7

ALTERNATIVE PROPULSION SYSTEM CONFIGURATION LAYOUTS FOR CONVENTIONAL DESTROYERS

H = HEATER, B = BEARING, G = GEARBOX OR GENERATOR, P = PRECOOLER, I = INTERCOOLER,
T = TURBOMACHINERY, RG = REGENERATOR, M = MOTOR, RF = REFRIDGERATION SYSTEM



79-05-83-9

FIG. 2.9

PHASE III-3

IDENTIFICATION OF CRITICAL COMPONENT TECHNOLOGIES

After completion of Part II of this program (Ref. 3.1), which provided a conceptual design for the selected propulsion system, specific identification of the required critical component technologies was then completed. The first portion of this task was performed by reviewing recent results and extensions of applicable technologies, and then the technological barriers and constraints of the selected propulsion systems were identified. Subsequent sections present the results of additional studies which were undertaken to examine possible methods of removing these barriers and constraints, and to estimate the required test and development costs and schedules.

3.1 Recent Results and Extensions of Technologies

In view of the time which has passed since the initiation of this program, reassessment of the expected status of technology in the late 1980's is timely. Accordingly, extensions of technologies in both the closed- and open-cycle gas turbine (CCGT, OCGT) fields were examined. The status of OCGT technology is presented first, since much of the expertise in this field is directly transferable to the CCGT field.

3.1.1 Open-Cycle Gas Turbine Technology Status

As reported in the Part I report (Ref. 3.2), the critical technology for open-cycle gas turbines is concerned with cooling the hot-section components. This is still true today. Since it is unlikely that ceramic hot-section hardware will be in production by 1990, the critical technology must be directed toward cooling metals (superalloys) to assure acceptable durability for these high-cost parts while not drastically penalizing performance.

A few notable changes have occurred since publication of the Part I report evaluation, and these are, in part, due to several new studies and design efforts promoted by the Department of Energy (Refs. 3.3 and 3.4). These changes result from a reconsideration of both old and new concepts for turbine blade cooling, particularly those applicable to stationary power plants where weight is not a critical factor. As a result of these changes, the projections of turbine inlet temperature increases through the 1980's have changed from those presented in Ref. 3.2 to those now shown in Fig. 3.1. Since the amount of parasitic cooling air which must bypass the combustor will be reduced through the use of these new concepts, the projection for maximum pressure ratio in the compressors of open-cycle gas turbines has increased slightly, as shown in Fig. 3.2.

The impact of these OCGT changes on open-cycle gas turbines will be to increase the efficiency of land-based applications. The impact of these changes on the conceptual closed-cycle gas turbine design of Part II should be to improve the performance of the fossil-fired heater. However, these changes such as water cooling, will increase the complexity and weight from the levels of the current OCGT designs. Incorporating these technologies in a CCGT system might be more advantageous since the overall durability of certain fossil heater subsystem components (such as the blower-drive turbine) could be improved.

3.1.1.1 Combustor Exit Temperature Projections

The latest projections for combustor exit temperatures shown in Fig. 3.1 are changed slightly from a similar projection presented in the Part I report (Ref. 3.2). The band of temperatures expected for commercial aircraft has been reduced slightly in the 1990 time frame, while that for both the military and industrial gas turbines is still expected to achieve approximately the same levels of temperature as predicted earlier. These projections are the result of recent studies, e.g., the Energy Efficient Engine Program (Ref. 3.4), where it has been found that cooling air requirements must be carefully controlled and leakage paths carefully designed to provide both increased performance and acceptable durability. These considerations indicate that for the amount of cooling air which is reasonable to use in commercial aircraft gas turbines, the maximum combustor exit temperature which can be attained is expected to be approximately 100 degrees lower in 1990 than previously anticipated at the time the Part I report was issued. The projections for military aircraft engines are unchanged since these engines are designed for different mission requirements and in such cases, it is felt that large amounts of cooling air and high combustor exit temperatures can still be justified.

In the case of industrial gas turbines, the need for high efficiency and desire for high durability are even more critical than in commercial aircraft. The recent reconsiderations of cooling air technology would have lowered the projection for industrial gas turbine combustor exit temperature had it not been for alternative cooling concepts which are possible in land-based systems. Concepts such as reducing the temperature of the cooling air before it enters the high-pressure turbine stators or rotors, or using water for cooling these same parts, should allow cooling air mass flows to be reduced signficantly from the levels assumed in the technology assessment presented in the Part I report (Ref. 3.2). As a result, the projected combustor exit temperature in 1990 is unchanged for industrial gas turbines.

These additional cooling concepts cannot be used in commercial aircraft because of the required extra weight of heat exchangers and accessory equipment. The acceptability of using these concepts in ships which use open-cycle gas turbines is also in question because of the weight, volume, and accessory

requirements of the large open-cycle gas turbines. In contrast, these new cooling concepts might improve the marine acceptability of a fossil-fired, closed-cycle gas turbine system by providing improved methods of operating the heater. In the fossil-fired CCGT, only a small open-cycle gas turbine is needed to provide pressurized combustion air for the CCGT heater. This small gas turbine could use these new gas turbine cooling concepts to improve the OCGT durability, while requiring much smaller accessory cooling air components than when a large OCGT is used as the prime mover. Furthermore, the technology gained from several current industrial gas turbine studies (c.f., Refs. 3.3, 3.4, and 3.5) in assessing the potential for burning poor-quality petroleum fuels or coal-derived fuels (which usually contain many more harmful constituents such as vanadium, sodium or sulfur) will be beneficial to the design of the closed-cycle heater discussed in the Part II report (Ref. 3.1).

3.1.1.2 Material Availability

All of the projections made for open-cycle gas turbines are based on the assumption that materials such as ceramics (which have a much higher feasible operating temperature and thus will require greatly reduced cooling air flows) will not be available for use in the hot sections before 1990. The only ceramic materials included in the cooling concepts projected for 1990 OCGT's are thermal barrier coatings which were assumed to be selectively applied.

Taking these limitations in ceramic materials into consideration, Fig. 3.3 presents an updated projection for the material advances expected, and those types of alloys believed suitable for hot section applications. When this information is compared with that in a similar figure from the Part I report (Ref. 3.2), it can be noted that the projected maximum temperature capability for nickel and cobalt base superalloys is increased slightly in the 1990 time frame due to continued improvements in material properties (Ref. 3.6). It can also be noted that the chromium, columbium, and titanium (beta) alloys do not appear in this figure. These latter alloys were removed since material development in the past few years has indicated that the problems associated with their use are great and the ability to overcome these problems will probably not be attained before the late 1980's. The problems of embrittlement in chromium alloys and of oxidation in columbium alloys seem unreasonably difficult to solve, at least in comparison with burgeoning developments in other superalloys and ceramics. Indeed, for chromium and columbium alloys, the very availability of these elements is questionable. The projections and applications of ceramics will be discussed further in the sections on closed-cycle technology.

3.1.1.3 Compressor Technology Projections

For open-cycle gas turbines, incorporating the refined cooling concepts of commercial aircraft engines, pressure ratio levels over 30 to 1 (Ref. 3.4) for a simple cycle OCGT will again be advantageous. Such simple-cycle engines might

be used in commercial aircraft or in electrical peaking plants or possibly even for selected ship propulsion systems. However, when a combined-cycle system (using an OCGT and a waste heat recovery steam boiler) is examined, the pressure ratio for maximum efficiency occurs at approximately 19:1 or 20:1 (Ref. 3.3). These observations indicate that compressor technology should not be a limiting factor for closed-cycle systems or even for open-cycle systems in the late 1980's. Consequently, the potential limit for maximum compressor pressure ratio, as shown in Fig. 3.2, is now expected to be greater than that presented in the Part I technology assessment.

The efficiency predicted for late 1980's compressor technology is basically unchanged from that presented in the Part I report (Ref. 3.2). That is, the attainable polytropic efficiency should exceed 90 percent, and the adiabatic efficiency used in the Part II CCGT conceptual design (Ref. 3.1) should also be attainable. Except for the hot-section cooling flow requirements discussed earlier, the projections for other turbomachinery design parameters presented in Table 3.1 are also only slightly changed.

3.1.1.4 Degraded Fuel

Considerable effort within the gas turbine industry is being expended in the study and improvement of open-cycle gas turbines capable of using degraded fuels in the future. The Bunker fuels have been studied and utilized with some success in many past gas turbine applications, but future gas turbines may even have to use fuels which are derived from coal. These coal-derived fuels often contain more impurities which are harmful to the gas turbine than are present in current fuels. Coal gasification and fluidized bed studies of open-cycle gas turbines, Refs. 3.7 and 3.8, have also received a great deal of attention. Further work in these areas should benefit future closed-cycle applications as well as open cycle applications, since the basic technology should apply to the heater of the closed-cycle system where metals must operate at high temperature in corrosive environments.

3.1.2 Closed-cycle Gas Turbine Technology Status

As discussed in the Part I report, the most critical technology for closed-cycle gas turbine systems is that of the maximum cycle temperature. This temperature is limited to 816 C in this study by the material characteristics required at the metal temperatures encountered in the heater portion of the closed-cycle system. Ceramics were not used in either the turbomachinery or the heater sections of the conceptual, closed-cycle system design since recent deveopments (c.f., Ref. 3.9) indicate that progress in ceramic materials development will not be sufficient to allow for their extensive use for marine applications by 1990.

Other technical considerations which must be given careful design and development attention, but which should not present insurmountable problems,

include bearing and oil sealing systems, design, accommodations to helium gas flow dynamics, and automated control systems design. Each of these subjects will be discussed in more detail in the sections which follow.

3.1.2.1 Closed-Cycle Material Technology

The materials used in the hot sections of closed-cycle gas turbines are expected to be the same as those used in the hot sections of open-cycle gas turbines. In particular, metal temperatures in the heater of the closed-cycle system will be subjected to approximately the same metal temperatures as those in hot sections of open-cycle aircraft gas turbines. Furthermore, the combustion gas environment to which these metals will be exposed, means that the same hot corrosion and sulfidation problems which affect the OCGT, will have to be overcome in the closed-cycle heater.

As mentioned, ceramics were not included in the conceptual designs generated in this program. There appears to be general agreement throughout the industry that ceramics will not be available for use as turbomachinery airfoil sections before 1990, and even in the heater, the use of ceramics before 1990 is debatable. It appears that within a few years after 1990, ceramics may be incorporated into the hot section of closed-cycle gas turbine heaters, and this use may allow turbine inlet temperature and overall efficiency to increase. Should this occur, the other materials used in the closed-cycle turbomachinery may have to be reassessed.

Except for the post-1990 applications mentioned, there are several fundamental reasons why ceramics have not been selected for use in the conceptual designs presented. These are: (1) the poor shock load capability of ceramics; (2) the susceptability of ceramics to corrosion in the marine environment, particularly when poor quality fuels are used; (3) excessive leakage under high pressure due to porous nature of ceramics; and (4) limited mechanical strength for thin wall designs.

The shock loading which the marine propulsion system must endure may never be amenable to ceramic materials. Current systems are designed to withstand loadings in excess of 20 g, and equipment which has been under battle conditions has experienced shock loads in excess of 100 g's. Consequently, it is likely that only ceramic thermal barrier coatings will find successful application in the marine environment.

A fact which is often overlooked in assessing ceramics is that they also are prone to corrosion. Vanadium, sulphur, and alkali attacks can be as detrimental to ceramics as they are to superalloys (Ref. 3.10), and when one considers the fact that superalloy development programs have been directed toward solving this problem for twenty years, it seems extremely optimistic to assume that ceramic development can overcome corrosion problems in less than ten more years.

Thermal shock is another consideration which has hindered ceramic use. Although the thermal shock characteristics of some ceramics, such as silicon carbide or silicon nitride, may prove acceptable prior to 1990 (Ref. 3.9), it is likely that special operating procedures will still be required to minimize thermal shocks and provide long-life even for these ceramic materials. Accordingly, it is unreasonable to project a widespread availability of ceramics for production systems before 1990. Although considerable development of ceramics is in progress and being planned (c.f., Ref. 3.9) to deal with the similar problems which would be encountered in a closed-cycle fossil-fired heater, bringing these developments to a state-of-the-art consistent with materials in production engines will likely require more than ten years of effort.

Other materials problems mentioned in the Part I report, such as self-welding of metal parts, and the unknown nature of creep growth in the helium environment, appear to be less of a problem than originally thought. Recent reports in these areas (Refs. 3.11 and 3.12) have allayed fears in these regards. Indeed, the operation of the closed-cycle system in Oberhausen, Germany in recent years (Ref. 3.13) has indicated that cycle temperatures near 800 C have been attained without serious problems.

3.1.2.2 Helium Flow Dynamics

Another technology discussed in the Part I report (Ref. 3.2) is that of helium flow dynamics, where there is limited availability of experimental test data. Since the Part I report, new work has been completed in this area by several organizations. The P&WA Government Products Group of UTC has studied the preliminary helium turbomachinery designs of the Part I report and has been able to reduce significantly the number of stages required in the turbine. Results of this effort are seen in the conceptual design of the turbine presented in the Part II report (Ref. 3.1). A testing program funded by the Office of Naval Research (Ref. 3.14) also investigated the correlations between analytical predictions and test data for helium flow characteristics. Further, the German CCGT test facility, designated "HHV" (Ref. 3.13), has begun testing full-size turbomachinery hardware. Thus, the potential for obtaining good test data for helium turbomachinery and flow dynamic performance over the next five years is encouraging.

3.1.2.3 Control Technology Status

The operations of closed-cycle systems in both Japan and Europe in recent years (Refs. 3.13 and 3.15) have done much to increase the validity of projections made in the Part I report (Ref. 3.2). One of three Japanese closed-cycle systems was operated as late as 1976. Two of the systems used gas as a fuel, and one system used diesel oil to heat the closed-cycle gas in a heater. The successful operation of the gas-fired systems has indicated that control systems

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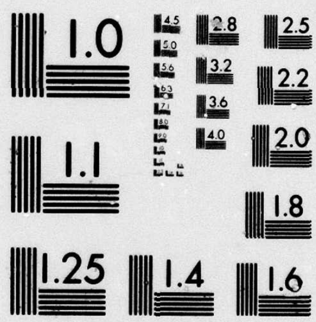

MICROCOPY RESOLUTION TEST CHART
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can be made to work reliably. The oil-fired system used almost all of the potential control modes previously discussed in Refs. 3.1 and 3.2. These included both inventory and temperature control in an attempt to overcome design deficiencies which existed in that system. Plants in Germany have also continued to operate successfully (Ref. 3.13), using the control modes discussed in the Part I and Part II reports (Refs. 3.1 and 3.2).

Much work still remains in the development of control systems and methodologies for accurately and effectively changing the power level of closed-cycle systems, particularly when used for marine applications. Further development of control systems would be necessary, since the conceptual design presented in the Part II report requires rapid power turbine speed changes to control the rotational speed of the directly-coupled propeller. This variation of output speed is different from that experienced in the Japanese and German systems where the output speed is generally maintained constant. In fact, the Oberhausen plant has experienced difficulties with plant transients, particularly during startup and shutdown. Several times, this plant has encountered problems severe enough to cause an extended shutdown. These problems included oil contamination of the gas path which occurred during these transients as a result of defective oil compartment seals and failure of the bearings to function properly. The solution to these problems has been a change in the design of the seals and bearings and also a modification of the transient control methodologies and procedures (Ref. 3.13). The status of bearing and seal technology are discussed in the next section.

3.1.2.4 Bearing and Seal Technology Status

The requirements for the bearings and oil compartment seals in a closed-cycle system have been highlighted as a critical technology in several previous programs including the LWSPS, Part-I (Refs. 3.2 and 3.16). The CCGT plant which is operating in Oberhausen, Germany is said to have experienced some problems with oil contamination of the gas path as well as bearing failures (Ref. 3.13). The Japanese CCGTs experienced turbine erosion and corrosion due to the presence of foreign particles in the closed-cycle gaspath, although in this case, it was believed that the damaging powder was attributable to insulation material which was exposed to the gas flow (Ref. 3.15).

In the American High Temperature Gas-Cooled Reactor (HTGR) Program (Ref. 3.16) extensive considerations have been given to the design of both the seals and the bearings based on the experience with the German and Japanese CCGT operations. The HTGR-CCGT program is particularly concerned with contamination of the gaspath since this closed-cycle system is designed to be integrated directly with a nuclear reactor heat source. Any contamination of the gaspath in this system could cause the expensive turbomachinery and the remainder of the power conversion system to become radioactive and subsequently unserviceable.

In the conceptual design of the 80,000-shp LWSP-CCGT system (Ref. 3.1) the oil leakage problem is not regarded to be as critical as in the nuclear-powered, direct-cycle HTGR-CCGT system. However, the Japanese experience with the marine closed-cycle gas turbine (Ref. 3.15) indicates that erosion caused by condensed moisture and foreign particles can also drastically damage the rotating parts.

The technologies of using a buffered seal concept, as presented in the Part II conceptual design of this program (Ref. 3.1), coupled with an in-line purification system for the working gas, can potentially eliminate or at least minimize the contamination and erosion problems. However additional development and testing should be performed to gain confidence in the ability of these seals and purification systems to operate satisfactorily under the rapid transient conditions required of naval ship operation.

Based on the foregoing discussion, most of the bearing and oil system technical difficulties are expected in the area of bearing compartment seals and not with the bearings themselves. Although the Oberhausen plant did experience problems with journal bearings, the currently available designs (Ref. 3.17) and technology are considered to be capable of using successfully both tilting pad journal and thrust bearings such as those incorporated in the Part II conceptual design.

Additional bearing design considerations which must be carefully considered before actual hardware is fabricated are the location and number of bearings. The positioning of the bearings and the manner by which the turbomachinery is joined can have a significant effect on the critical speeds of the turbomachinery spools. It is possible that this type of problem may have caused some of the bearing damage encountered in the Oberhausen plant. The HTGR-CCGT Program (Ref. 3.16) has made several turbomachinery design modifications to accommodate the critical speeds. Recent design changes in this program have shortened the gas turbine length considerably and changed the number of bearings to both reduce critical speed problems and improve maintenance characteristics. However, the resulting design is still one which encounters critical speed modes at shaft speeds below the design point condition.

This design approach may be acceptable for a utility electric power generating application where the output speed is maintained constant. However, in a naval propulsion engine design it would be undesirable to have a significant critical speed mode within the operating range of the propulsion system since this might have a detrimental effect on the operational characteristics and reliability of the system. For the mechanical transmission design presented in Part II (Ref. 3.1), where turbine speed is directly proportional to propeller speed, this obviously places additional constraints on the bearing arrangements for the turbomachinery. Thus, the critical speeds must also be considered in a future detailed design of a closed-cycle system for ship propulsion.

3.1.2.5 Ducting Requirements and Pressure Loss Characteristics

In several of the closed-cycle systems which have been built and operated, it has been found that maintaining low cycle pressure loss can be a difficult technological problem. A Japanese closed-cycle system (Ref. 3.15) encountered such excessive pressure losses that the overpressurization of the system necessary to provide desired performance, eventually caused turbomachinery failure because of excessive stresses. Also, the most recent efforts in the HTGR-CCGT Program (Ref. 3.18) has resulted in a redesign of the inlet and outlet ports and of the ducting for the turbomachinery, in the expectation that the pressure losses would be lower.

The Part-II conceptual design (Ref. 3.1) has used a unique method of bringing the helium gas into and out of the turbomachinery spool. This method has been documented in a patent application (Ref. 3.19) which will be assigned to the Office of Naval Research as a direct result of this program. Discussions with P&WA indicate that this method may have promise for future closed-cycle and perhaps even industrial open-cycle gas turbine applications, particularly those which require intercooling. This concept would enable design of a shorter and more compact gas turbine, particularly desirable for ship propulsion applications.

3.2 Technological Barriers and Constraints of the Selected Propulsion System

Although the recent developments discussed in the previous section could be beneficial in minimizing the technological problems of closed-cycle gas turbine systems, many technical barriers and constraints remain. These barriers and constraints are presented in Table 3.2 and are discussed in the following three sections on turbomachinery technology, heat exchanger technology, and overall system technology.

3.2.1 Turbomachinery Technology Barriers

The turbomachinery technology which might limit the development of closed-cycle gas turbines can be allocated into several areas. These are the helium flow dynamics, the ducting and inlet/outlet losses, and the critical speed and bearing problems.

3.2.1.1 Helium Flow Dynamics Barriers

Since helium offers excellent heat transfer characteristics which can lead to a reduction in the size of the heat exchangers needed, many closed-cycle

gas turbines are expected to utilize helium as the working fluid. However, turbomachinery designs are quite complex, thereby requiring extensive testing to understand the steady state and transient performance characteristics of the gas path components. The characteristics of boundary layer formation and stall are particularly important. Even the desired level of blade loading and effect of blade shape in a helium turbomachine are far from completely understood. It is therefore imperative that more understanding be gained of helium flow dynamics if closed-cycle systems are to use helium as the working gas. However, even with an intensive development program, it is not likely that the flow dynamics of helium will be as well understood and developed by the late 1980's as are current aerodynamics. If this proves to be true, the flexibility in designing the helium turbomachinery will be quite limited. As a consequence, the number of stages required in the turbomachinery may be higher than optimum and the surge margin may be uncertain. Even the number of choices for possible redesign to minimize critical speed problems will be limited.

3.2.1.2 Ducting Considerations

The performance of closed-cycle systems has long been known to be critically dependent upon the total presure loss encountered throughout the entire flow loop. Unfortunately, there are very few analytical procedures available to predict with reasonable accuracy the losses which are encountered in inlet and outlet ports of either the turbomachinery or the heat exchangers. When diffusers and sudden transitions or turns are required in the gas loop, it has been a common practice to resort to model test data or even full-size component test data for design predictions rather than analytical estimates. Recent work on the HTGR-CCGT program (Ref. 3.18) has highlighted the need for development in this area. It is desirable that any closed-cycle system design be preceded by an early test of the ducting arrangement to avoid later major rearrangements or internal component modifications. In particular, the methods which allow the gas to enter or leave the turbomachinery and heat exchangers should be carefully studied, and general components should be arranged to provide the lowest pressure loss practical.

The containment of large rotating turbomachinery parts following failure may also be a significant technological barrier. The analytical methods available to predict the penetration of surrounding cases by failed rotating parts are not an exact science. Additional work would be required either to improve these analytical methods or to perform additional testing on specific designs to evaluate their safety factors.

Noise generation in a helium closed-cycle system has also been found to be more severe than expected (Ref. 3.13). Safe engine-room environmental conditions may only be possible after developing new criteria for sound insulation designs.

3.2.1.3 Bearings, Seals and Critical Speeds

While it is unlikely that bearings or seals will present a significant technological barrier or constraint for the turbomachinery design, it is the lack of experience in relating the design to a demonstrated capability of these components under stringent naval propulsion system requirements which would hinder this application. Most tilting pad journal bearing manufacturers (Ref. 3.17) currently produce bearings which should be acceptable for the closed-cycle systems studied in the program. Sealing methods are also believed to exist which can be adapted to the fossil-fired, naval propulsion system.

An area of bearing technology which has not received sufficent attention is the interaction of the critical (or "resonant") speeds of large turbomachinery with the widely varying rotational speed requirements needed for naval propulsion systems when using mechanical transmission systems. Critical speeds could therefore significantly inhibit naval applications of CCGT since almost all of the large industrial gas turbines built, both open- and closed-cycle, are designed for a single operating speed at the power turbine shaft. Many of these designs have very long center lines, and their components are so massive that critical speed modes occur at speeds lower than the design point speed. In utility applications this might be tolerable since a very short period of time is spent at these speeds. In fact, many utility and industrial operating procedures are established to minimize the time spent at selected rotational speeds. Such procedures may not be possible in a naval application and even short times spent at these speeds could have a destructive effect on the seals needed to prevent oil from entering the gaspath.

Thus, the design of a reliable bearing arrangement may be a significant technological barrier to the successful utilization of closed-cycle systems coupled with mechanical transmissions for naval propulsion. This barrier may be lowered by providing developmental test data in the next few years on models of the system designs needed. However, there will be little substitute for full-scale operational experience in providing a successful closed-cycle gas turbine design in the future.

3.2.2 Heat Exchanger Technology Barriers

Two areas of heat exchanger technology may constrain the widespread adoption of the selected propulsion system. These are the materials used in the heater construction, and the fabrication techniques needed for the regenerator and the other heat exchangers. The selected propulsion system uses the material temperature limits of superalloy metals, while the design of the regenerator heat exchanger requires mass-production of a unit which contains over 48,000 tubes. These barriers are discussed in more detail in the sections which follow.

3.2.2.1 Cycle Temperature Limitations

Probably the most apparent performance barrier for closed-cycle gas turbine systems is that imposed by the maximum gas temperature in the closed-cycle loop. This maximum temperature occurs at the heater outlet where the recirculating gas is normally brought to a temperature limited by the materials in the heater itself. When the heater contains superalloy metals, the maximum average metal temperature allowable will usually be on the order of 800 to 950 C (1700 to 1800 F). This limit is due to a combination of the material stress encountered, the creep which results, and the corrosion limits which must be observed on the combustion gas side of the heater (if the heater utilizes a fossil-firing system). In contrast to the situation in an open-cycle gas turbine hot section, the metal temperatures in the closed-cycle heater will always be higher than the average working gas temperature. Thus, the metal temperature limits would limit the turbine inlet temperature to approximately 800 C (1500 F) for a CCGT using a metalic heater. Attaining this temperature in a fossil-fired heater, will also require advances in material hot corrosion resistance, as well as improvements in coatings which protect the base material.

3.2.2.2 Operational Characteristics of the Hot-Gas Heater

The heater selected for the LWSP-CCGT propulsion system has not been given the same extensive Naval service as have steam boilers. It took many years to appreciate the operational limits of steam boilers, yet it is unlikely that a similar time span will be allowed for determining the characteristics of the hot-gas recirculation heater needed for the fossil-fueled CCGT. Consequently, a significant technological barrier faces the goal of incorporating the LWSP-CCGT propulsion system in 1990 Naval ships. Not only must the design of the hot-gas heater have to take into consideration almost all the complex operating conditions which will be required of the heater, but the majority of these will have to be experimentally verified. Such a verification program will be extremely difficult to accomplish, since there will likely be only two to three years available to test the integrated propulsion system (heater plus turbomachinery and heat exchangers) prior to 1990.

Ceramics might be used in land-based, closed-cycle heaters by 1990 thereby allowing the use of increased material temperatures. However, in a naval environment where 20 g loading is not uncommon, it is unlikely that ceramics will be applicable by 1990. Indeed, ceramics may not even be able to provide acceptable life in a fossil-fired, land-based heater, since the typical alkali deposits resulting from the use of poor quality fuels can cause hot corrosion of ceramics just as in superalloys (Ref. 3.10).

Thus, the turbine inlet temperature for fossil-fired CCGT systems still appears to be limited to approximately 816 C (1500 F) for the 1990 time period. As shown in Fig. 3.4, the progresssion of turbine inlet temperatures expected for CCGT's has been modified slightly from that presented in the Part I report.

Data in this new figure differentiate between the temperatures attainable with superalloys and those attainable with ceramics. When ceramics become available, probably after 1990, the turbine inlet temperature can be expected to increase dramatically in a few years time, for example, from 800 C to 1000 C.

3.2.2.3 Heat Exchanger Fabrication Technology Barriers

Another more mundane, but no less important, technology needed to build the conceptually designed fossil-fired, closed-cycle gas turbine, includes that associated with the fabrication and servicing procedures for the heater and regenerator. The tube sizes used in the Part II (Ref. 3.1) conceptually designed heat exchangers are smaller than those commonly used today in industrial or naval systems. The regenerator which uses tubes of 6.35 mm O.D. (0.25 inches), and the heater which uses tubes of 8.89 mm O.D. (0.35 inches), present stringent manufacturing requirements uncommon in present production practices. Over 48 thousand 6.5-meter long tubes are required in the regenerator alone, while the heater requires over 30,000 tubes at a length of over 6 meters. The support of these long thin tubes will have to be given careful design and development attention in order to provide acceptable durability in the naval environment, and the maintenance practices for servicing such designs may require new techniques.

3.2.3 Overall System Technology Barriers

The propulsion system selected for the high-speed destroyer in the Part II conceptual design (Ref. 3.1), will encounter technological barriers and constraints in areas beyond the power conversion system. In particular, the supercavitating propeller, the epicyclic gearbox, and possibly even the propeller shaft thrust bearings, require designs which are beyond the current state of the art. Probably the most significant of these barriers exists in the area of supercavitating propellers since the 59 MW (80,000 hp) size required for each propeller is well beyond any currently available supercavitating propeller power (approximately 30,000 shp). Attaining the 65 percent efficiency projected for this propeller will also require considerable development.

In the area of epicyclic gearboxes, it has been observed that a gearbox which would meet the specific needs of the Part-II conceptual design has not been manufactured. However, it appears that the extension of current technologies, such as the Government-sponsored development effort of high-powered gearboxes by Curtis-Wright Corporation (Ref. 3.20), could readily remove this barrier.

Control systems which coordinate the CCGT system operation could also present significant barriers. The interactions of the heater, turbomachinery, heat exchangers, and propeller system must all be accommodated in such a manner that the system will successfully meet the marine and naval requirements. As discussed in a previous section on the recent extensions of this technology,

the ability to make rapid transients has not been proven in most previously operated closed-cycle systems. Therefore, to accomplish this, the design will have to consider the dynamic characteristics of all the closed-cycle components. Unfortunately, the ability to predict the stability of such rapid changes is a very uncertain matter. Testing of these designs will be required at the earliest possible date.

The technological status of electrical transmission systems is discussed in Section III-1 of this report, and it is obvious that there are barriers in superconducting and SEGMAG electric transmission technologies which will have to be overcome before they can supplant the more well understood mechanical transmission systems. Lightweight electrical transmission concepts in general are not advanced to the same stage of development as mechanical transmissions. The first subscale SEGMAG machines are currently under construction (Ref. 1.18) but have not yet been demonstrated. AC superconducting development has concentrated on utility applications for generators; little if any hardware has been demonstrated which is applicable to ship propulsion motors. Of course DC superconducting development has produced many expensive demonstrations, but it appears that much work remains before this technology will reach the readiness of mechanical transmission systems. However, the electric transmission systems offer operational advantages or even may allow elimination of some of the other barriers, such as the closed-cycle gas turbine systems transient control and critical speed problems, which have been discussed thus far.

3.3 Removal of Technological Barriers

The sections which follow discuss methods of removing the technological barriers identified in the previous section. These discussions are presented in three separate sections: turbomachinery technology; heat exchanger technology; and overall system technology. Both a preferred barrier removal method and alternative methods using substitutes to provide a demonstration system are discussed.

3.3.1 Turbomachinery Technology

Barriers for the advancement of helium turbomachinery technology can be separated into five areas: helium flow dynamics; transient and dynamic operating characteristics; pressure loss; sealing and bearing requirements; and critical speeds. Methods for overcoming these barriers, or avoiding them, are presented in Table 3.3 and are discussed in the section which follows.

3.3.1.1 Removal of Helium Flow Dynamics Barrier

As discussed previously in Section 3.2.1.1, the most significant turbomachinery technological barrier is the lack of data on helium flow dynamics. This problem might be resolved if extensive testing were performed on blade

"airfoil" shapes to establish their "aerodynamic" performance characteristics when operated in a helium environment. Both stationary and dynamic testing would have to be performed on these blade shapes. Furthermore, the interaction between blade rows would also have to be established before components such as the low and high compressor could be expected to function properly as an integrated unit.

One alternative, which would not require such extensive testing, would be to use air as the working fluid. However, the use of air would significantly increase the size of the heat exchangers required. The advantage of using air would be that the basic aerodynamics and stage matching characteristics are well known and, therefore, much less basic testing would be required prior to making a demonstration of CCGT capabilities.

3.3.1.2 Removal of Transient and Dynamic Operational Characteristics Barriers

To overcome the barriers associated with the transient and dynamic operational characteristics of the turbomachinery, it is anticipated that a significant amount of subscale testing of integrated turbomachine components would be required. At a minimum, testing to establish such characteristics as stall and transient limitations would include operation of each of the low and high compressor sections through an extensive range of operational conditions. Testing of the entire closed-cycle gas turbine power conversion system would be desirable, although full-scale component testing in this manner would be extremely costly. Obtaining this type of information through testing of a subscale system would be more cost effective since it would reduce the cost of the components while still allowing for a significant evaluation of component interactions and transient effects.

In lieu of developing helium turbomachine operational characteristics, a substitute design which uses air as the working gas might avoid these technological barriers. However, to predict confidently the transient and dynamic operational characteristics of even an air system, the turbomachinery would have to exist or else be extensively tested. A drawback to using existing turbomachinery would be a limited output power (approximately half of the 80,000 shaft horsepower designed for the helium closed-cycle gas turbine system).

3.3.1.3 Removal of the Pressure Loss and Ducting Barriers

The cycle pressure loss was found to be one of the most important performance factors in the Part I studies (Ref. 3.2). Signficant portions of the total cycle pressure loss are caused by ducting and transition regions such as in the inlet and outlet ports of the turbomachinery and heat exchangers. Since pressure losses in these regions are difficult, if not impossible, to predict accurately from an analytical standpoint, it is imperative that at the very

least testing be undertaken of subscale models of the ducting arrangements and transition region geometries. Some full-scale testing should also be expected to define and "fine tune" the pressure losses. A substitute development approach would be to use the first demonstration system to establish actual pressure loss without undertaking the subscale rig test and modifications. This full-scale development practice probably would lead to degraded performance for the demonstration unit, but the corrections required could be made in subsequent full-scale (production) units unless the problem required a major redesign of the turbomachinery, ducting, or heat exchanger housings. The subscale method has been assumed in the development plan presented later in this report.

The removal of barriers in the areas of "containment", both of failed parts and of noise, will only be accomplished through testing. Both of these technologies are not readily dealt with analytically.

3.3.1.4 Removal of Sealing and Bearings Barriers

The sealing and bearing designs of the closed-cycle helium gas turbine system present technological barriers as discussed in the previous section of this report. None of these barriers is expected to require new technology, and only adaptations and careful considerations of existing designs should be required. However, to assure that these designs are successful, component rig tests should be performed. These tests should simulate not only steady-state operation but transient operational conditions which may greatly exceed the steady-state design requirements. In particular, sealing arrangements, such as double buffered seals, should be evaluated in terms of their sealing capabilities, strength, reaction to natural frequencies, and durability. An alternate method which would avoid this technological barrier would be to utilize existing turbomachinery designs which have proven sealing and bearing designs. As pointed out previously, the use of existing machinery would mean reduced power output.

3.3.1.5 Removal of Critical Speed Barrier

Critical speed problems could be severe in a marine operation because of the speed range over which the system is required to operate. Proper attention to this problem should result in several major turbomachinery redesigns, although the cost of such redesigns could be minimized if extensive critical speed analyses were performed as part of the initial design work. Again, the use of a proven or existing turbomachine design might allow avoidance of this critical speed barrier, although, existing designs should either be those which use air as a working gas or can be made to operate at a reduced speed and output level when using helium.

Another method which could minimize the critical speed problem would be the use of an electric transmission system. The electric transmission would

allow the turbomachinery rotational speed to be held nearly constant so critical speeds might be avoided or the time spent at critical speeds could be minimized.

3.3.2 Removal of Heat Exchanger and Heater Technological Barriers

There are basically four barriers to the heat exchanger technology which must be overcome in the closed-cycle gas turbine system evaluated here: the cycle temperature level; the heater operational characteristics; the fabrication costs; and the maintenance practices. The impact of these barriers on the CCGT and approaches to their removal are discussed in subsequent paragraphs. A summary of the methods needed to overcome or avoid these heat exchanger barriers is presented in Table 3.4.

3.3.2.1 Removal of Cycle Temperature Barrier

The performance of the CCGT system is thermodynamically limited by the maximum cycle temperature assumed for its operation. In this program, the 816 C temperature used for the design point turbine inlet temperature is greater than that which has been previously operated in many closed-cycle plants built in the past. Achievement of this temperature in a long-life design requires a background of material corrosion test results. Even the basic "hot-gas" heater concept would have to be evaluated through component or subscale tests to determine pressure loss characteristics, parasitic power loss characteristics, hot spot locations, thermal stress and shock problems, and combustor performance, to mention a few of the more critical heater problem areas.

During such testing, other new heat exchanger concepts including implementation flow distribution control and heat transfer augmentation should be evaluated, and even new materials, such as ceramics, should be considered for evaluation. In the event all of these barrier removal procedures prove to be unsuccessful, or too costly, a lower turbine inlet temperature might be substituted and/or considered in conjunction with improved heat exchanger performance (such as increased regenerator effectiveness). Improved heat exchanger performance, however, would likely require smaller heat exchanger tube sizes which probably would result in higher fabrication costs. Another method of accepting a lower turbine inlet temperature would be to add a topping cycle which would use the high-temperature energy from the combustor in a separate power conversion system (such as MHD or thermionic power system) while still allowing the lower temperature gas to pass through the CCGT system. Finally, of course a reduced TIT could be used without other design changes, if reduced output and reduced efficiency were acceptable.

3.3.2.2 Removal of Heater Operational Barriers

Little is known about the operating characteristics of the helium heater required in the closed-cycle gas turbine propulsion system. In fact, the only helium heaters operated to date have not been required to perform under

rapid transients which could be expected in destroyer ship applications. The extent of this technological barrier might be lessened if experience gained from closed-cycle systems were used. Therefore, it is important that the development of current helium systems, such as the HHV project at KFA, Julich in West Germany, be monitored closely. Should these existing systems, such as that at Oberhausen (Ref. 3.13), encounter unique problems which severely limit its transient operation, a significant amount of subscale testing of the LWSP heater systems would be required. Alternatively, if the existing helium heater systems encounter problems no worse than those for existing boiler designs, then the amount of development and subscale testing required to prove the LWSP concept might be reduced.

Regardless of which of these development tests is required, it should be recognized that extensive computer simulations of the control system and the interrelations of component operating characteristics will be required. In addition, corrosion testing, which would evaluate the effect of short-term transient over-temperature conditions, must be examined before the CCGT heater system can be expected to provide a long service life. Endurance testing should also be included in the development program of the heater to further quantify the expected life cycle cost problems. Finally, because of the use of a single large heater on each 59.7 MW (80,000 shp) propulsion system, a significant development effort must be undertaken to determine the consequences of part-load operation. In particular, the performance when very low heat input is required (when the ship is operating at speeds less than 15 knots, under 10 percent power) can be accurately determined only by actual hardware testing.

Many of these fossil-fired heater operational barriers could be avoided if a substitute heater system were used. A nuclear-fueled, high-temperature gas-cooled reactor system would be one alternative. The development of this concept is expected to proceed in accordance with Department of Energy efforts related to the high-temperature gas-cooled reactor (HTGR) program in power plants such as the Fort St. Vrain plant in Colorado (Ref. 3.16). A non-nuclear alternative or substitute also exists. This substitute would rely on conventional steam boiler technology to provide a helium heater which would be much larger than the compact CCGT design presented in the Part II report of this program (Ref. 3.1). The advantage of this alternative is that such a "boiler concept" would require a much less extensive development effort. In fact, there now exist closed-cycle systems which have used these types of heaters successfully (Ref. 3.13).

3.3.2.3 Removal of Fabrication Barriers

The compact heat exchangers designed in the Part II of this program (Ref. 3.1) use tubes as small as 6.35 mm diameter (0.25 inches) in a quantity and complexity unheard of in current industrial practices. If "hand-made" fabrication methods were used for this type of heat exchanger, it is expected that the fabrication costs would be unacceptable. Therefore, to utilize such compact

heat exchangers, automated fabrication processes will be required. Processes such as furnace brazing or automated, numerically-controlled welding, using laser or electron beam methods, might have to be adapted or developed for the LWSP heat exchanger designs.

A way of avoiding this technological development would be to accept higher volume and higher weight heat exchangers which incorporate more conventional fabrication processes. These processes would require the use of larger tube sizes which would cause the increase in heat exchanger sizes.

3.3.2.4 Removal of Maintenance Practices Barriers

The design presented for the CCGT heat exchangers not only affects fabrication processes, but also may require modifications to Naval maintenance practices. Maintenance considerations are a primary reason that the LWSP design uses separate intercooler, precooler, regenerator,and heater sections. Separating these components, rather than combining them into one envelope, should allow Naval personnel to maintain them in a modular and submodular fashion. The precooler and intercooler are probably small enough to be removed as an entire unit from the ship if a failure occurs within them. The regenerator is designed with modular sections which should expedite onboard service.

New training programs would undoubtedly be required to utilize onboard Naval personnel for these service operations in an efficient manner. Should it be desirable to minimize these procedural qualifications, the heat exchanger designs could be revised to closely resemble more existing heat exchanger components. However, again it should be expected that increased weight and volume would result.

An alternative to overcoming maintenance practices barriers would be the elimination of all onboard servicing. The entire turbomachinery and heat exchanger package, regenerator, cooler and intercooler, could be united in one envelope. Should any component within this envelope fail to perform to a minimum expected standard, the entire power conversion system would be removed and replaced as a unit. Servicing could then be performed at specialized maintenance facilities located throughout the world. This would still require revised Naval procedures and possibly large initial expenditures, but would not affect fleet personnel requirements.

3.3.3 Removal of Overall System Technological Barriers

The total ship propulsion system selected in Phase 2 of this report includes technological barriers beyond those related only to the power conversion system. Controlling of the overall propulsion system, transmission and supercavitating propeller development requirements, turbomachine containment limits, and shaft thrust bearing loads may all present significant technological

barriers to utilization of the referenced propulsion system. Discussions of potential solutions to these technological constraints, and of substitutes for the limiting barriers are presented in the paragraphs which follow; these are also summarized in Table 3.5.

3.3.3.1 Removal of Overall System Control Requirement Barriers

Maintaining stable control of any closed-cycle power system can be a sensitive process, since any disturbance within the system could influence all of the components throughout the system. In contrast to an open-cycle gas turbine control system, which can rely on fairly stable conditions at the inlet and exhaust for reference, the closed-cycle system does not possess a large and stable reservoir in the flow path to provide a reference point for dynamic control of the system. In addition, the rapid transient requirements expected on a high-speed destroyer indicate that extensive computer simulations will be required prior to hardware testing to overcome the control technological barriers.

Assuming that representative models can be developed for the majority of critical system components, use of computer simulations should enable investigators to identify and resolve the majority of system control barriers. However, test operation of a subscale system, and possibly limited operation of a full-scale system, should be planned to establish more completely the control technology. Of course, the results obtained from existing and forthcoming closed-cycle system investigations (Refs. 3.13 and 3.15) should also be monitored so that problems and solutions encountered in these investigations can be avoided in the closed-cycle propulsion system investigated in this program.

As a substitute for control technology improvements, several alternative control methods exist. For example, the closed-cycle gas turbine propulsion system could be operated under certain restricted transient guidelines. For example, manual control of inventory valves, cooling water flows, and heater fuel rates might be used while still allowing the ship to achieve the majority of the required or desired duty-cycle conditions. The use of an electric transmission would reduce the requirements of an all-encompassing control system. In such a system, the power conversion components can be treated mechanically independent of the propeller and ship requirements, thus simplifying the overall control problem. Expensive computer simulations might also be avoided by developing control philosophies and limitations along with the first demonstration model. However, this "cut and try" method of development is tenuous since the costs of potential hardware modifications not only may be extremely expensive but also time consuming.

3.3.3.2 Removal of Transmission Barriers

The selected reference propulsion system (Ref. 3.1) would incorporate an epicyclic transmission which could be developed from currently available

transmissions. This development is not expected to encounter any significant technological barriers, rather, it would be an extension of the capabilities of an already existing technology. As an example of this technology extension, the epicyclic transmission of the reference propulsion system would have to provide a reversing stage and two reduction stages within an envelope approximately 30 percent smaller than existing double-reduction reversing epicyclic gearbox sizes (Ref. 3.20).

A much more extensive development program would be required if the SEGMAG or superconducting electric transmission systems were to be utilized. In fact, this is one of the major reasons that the mechanical transmission system was selected for the reference high-speed destroyer propulsion system. However, if the necessary development programs were undertaken, an electric transmission system like the SEGMAG would be competitive with the mechanical gearbox transmission as seen in the rating matrix in Table 2.10.

Avoidance of both the mechanical and electrical transmission technological barriers might be possible by using technologies which already exist for offset and/or epicyclic mechanical transmissions. However, this would cause the total weight and volume of the transmission to be increased above the levels projected in Phase 2 of this report and consequently would cause a reduction in payload and/or endurance capability.

3.3.3.3 Removal of Supercavitating Propeller Barriers

No supercavitating propellers currently exist which would meet the needs of the reference high-speed destroyer propulsion system, and as a consequence, continued development and testing of this component would be required in order to allow utilization of the referenced propulsion system. The extent of this development program would depend on the amount and number of compromises in the actual propeller performance which can be accepted. For example, if an efficiency somewhat lower than that normally considered at design were acceptable, significant development cost and schedule savings might result. Similarly, if the overall attractiveness of a destroyer with four propellers were acceptable, the extent of the supercavitating development program required would be still further reduced.

Other approaches which would avoid this technology development would be to use water jet propulsion, if that concept becomes available, or to reduce the maximum required ship speed by approximately 10 percent to allow the use of advanced subcavitating propeller designs. For example, based on consultations with Naval architects (Ref. 3.21), a 45-knot, 56-MW, subcavitating propeller could be built based on existing technology.

3.3.3.4 Removal of Thrust Bearing Load Barrier

Consultations with the Naval architect consultants (Ref. 3.21) on this program indicate that a thrust bearing which will accept 260,000 pounds force

at 580 rpm (80,000 shp input) is beyond the state-of-the-art. Therefore, a detailed design study of this thrust bearing should be expected as a part of any future development program.

Alternatively, use of more than two propellers per ship could avoid the requirement for increasing the technological capability of thrust bearings. This is one of the reasons that ships with four propellers with 40,000 horsepower per shaft were considered earlier in this report. Both the propellers and the thrust bearings required for a four-shaft configuration are only slightly beyond the capabilities of current equipment. However, as noted in the evaluation-selection matrix (Fig. 2.4), multiple propeller configurations were only considered with electric transmissions, and the overall attractiveness rating of these systems was lower than those of two-propeller configurations.

3.4 Testing and Development Requirements

As was discussed in the previous sections, many of the components in the selected reference closed-cycle gas turbine propulsion system will require additional testing and development during the next ten years to allow their utilization in Navy ships by 1990. The subjects and requirements of these tests, which are summarized in Table 3.6, are discussed in a conceptual manner in the paragraphs which follow; a more detailed discussion is presented in a subsequent section which describes the research and development schedules and cost estimates.

3.4.1 Turbomachine Verification and Basic Helium Flow Dynamics Development Requirements

As in any new turbomachine design, the helium CCGT-LWSP turbomachine must undergo demonstration testing prior to its shipboard installation. However, prior to fabrication of the first full-sized, closed-cycle gas turbine propulsion system, many more basic tests are required. As discussed in the sections on barrier removal, these tests should start with the gathering of basic flow dynamics data for both stationary and dynamic operation in a helium environment. These tests should start with the accumulation of data on the most promising blade foil shapes. Testing should then rapidly proceed directly toward evaluating the effects of modified foil shapes. This basic flow work should include identifying the characteristics of the boundary layer, endwall effects, recirculation, trailing edge and leading edge radii, tip clearances, and blade platform configuration, as well as the standard "aerodynamic" meanline flow parameters.

Following the basic data accumulation and initial design stages, rotating component tests should be performed with both single-stage rotors and multiple-stage rotor assemblies. These tests will provide important information for subsequent testing of entire compressor component sections. In particular,

these tests should identify the interaction between stages, and some of the transient characteristics of the overall component assembly, as well. Much later in the program, the integrated operation of the low and high compressor sections and two turbine sections, will be tested at conditions which simulate installed inlet and outlet duct flow characteristics. Both the initial single stage tests and subsequent spool tests might be performed in facilities such as the Pratt & Whitney Aircraft Wilgoos Laboratory, or the Government-owned Tullahoma facility.

In the turbine section, the heat transfer coefficients in the boundary layer are extremely important because of accommodating localized hot spots and cooling the internal cavity. Of particular concern is the blade-to-disc attachment region where the disc temperature must be maintained several hundred degrees cooler than the average blade temperature. The heat transfer characteristics of the compressor drive turbine and the free power turbine should also be examined.

3.4.2 Material Property Testing Requirements

At first, it might appear that the maximum cycle temperature (816 C) in the CCGT system would not cause any material problems. However, the use of a fossil-fired heater indicates that metal temperatures in the heater will be at or beyond the safe experience limits of even superalloys. Hot spot metal temperatures might approach 1000 C. Therefore, designing for a 30 yr. life in this environment will probably require a small safety factor. Consequently, testing of superalloys at this temperature, particularly those materials designated in the Part-2 heater design (Ref. 3.1), will have to be carefully tested. In particular, the corrosion effects created by the projected use of future fuels should be thoroughly evaluated.

The helium environment may also affect long-term material properties. While some work has been directed toward evaluating these effects (Refs. 3.16 and 3.22), additional testing and development should be performed to help guarantee the service life of the closed-cycle gas turbine system.

Thermal stresses, experienced both at steady state as well as during transients, must be carefully considered in the heat exchanger designs. However, even though these stresses are considered analytically, a test program is invaluable for determining the correlation between the predictions and actual experience. For example, open-cycle gas turbine regenerator designs which have evolved over the past ten years have been known to exhibit inadequate rapid transient operation (Ref. 3.23).

Ceramic materials offer properties which are of great promise to closed-cycle gas turbine systems. The inherent ceramic capability to operate at higher temperatures would make the closed-cycle system more efficient and possibly even lighter in weight. However, it is likely that extensive R&D

testing would be required to bring ceramic alloys to the state of development currently recognized for superalloys. Factors such as impact loading, thermal shock, and corrosion resistance to poor-quality fuels, must be more well known before a ceramic-based design could be considered for a 30-year life with the same confidence as a superalloy design.

3.4.3 Pressure Loss and Ducting Development Requirements

Since it is difficult to predict with accuracy the pressure losses through transition regions such as at the component inlet and outlet ports, and through some of the unique geometry configurations included in the referenced design, it is expected that testing and development will be required for determining these pressure loss characteristics. Subscale model testing is anticipated to be sufficient to estimate these losses accurately.

Other areas might require full-scale testing such as where losses occur due to weld-joint roughness and valve body discontinuities, and the basic heat exchanger core losses should also be considered for experimental verification. Although these losses might be predicted fairly accurately once a final design is completed, the criticality of pressure losses in general, and the magnitude of the losses in heat exchangers, indicate that testing would be very desirable.

Subscale testing and monitoring of foreign developments might also help understand the turbomachinery containment and noise problems. However, no substitute will exist for full-scale failure testing and noise monitoring of demonstration units.

3.4.4 Control and Transient Operation Development Requirements

While extensive computer modeling and simulation of the power conversion system control system can minimize the testing and design revisions required during the development program, it is still likely that testing of actual hardware will be required. However, this testing need not be performed exclusively on full-scale components. A subscale model would probably be adequate to verify the basic control process. Interaction of the various components and transient limitations, such as the stall characteristics of the turbomachinery, and the mechanical characteristics of the system valves and heat exchangers, should be better understood after operation of such a subscale system.

The characteristics of the reference LWSP system heater design should be tested, developed, and demonstrated before the integrated propulsion system is operated. Not only should the transient characteristics of the heater be investigated, but the partload limitations and potential modifications required should also be established. The duty cycle of the high-speed destroyer requires that a significant amount of time be spent at power levels under 10 percent of

maximum power. The successful utilization of the CCGT system may, in fact, depend on how well the system will operate under both low and moderate power conditions, i.e., for in-port manuevering or convoy escort duty. The possibility of constructing and testing a subscale heater prior to the full-scale tests should also be considered, although program time limitations may preclude this phase of testing.

3.4.5 Sealing and Bearing Development Requirements

The seal and bearing technology barriers referenced in the previous sections can be adequately resolved with full-scale rig testing. The size of these components is not extensive, and therefore a full-scale test program should be cost effective without subscale models. Subjecting these individual seals and bearings to their expected design and transient conditions should preclude significant problems when they are operated in the integrated propulsion system. For this purpose, a full range of expected pressures, temperatures, and leakage flow rates, in addition to the mechanical speed requirements, should be simulated in both performance and endurance testing.

3.4.6 Supercavitating Propeller Development Requirements

The high-speed destroyer concept considered in this report must rely not only on a lightweight, compact propulsion system, but must also be matched with an appropriate thrusting device. The supercavitating propeller design indicated on the high-speed destroyer is well beyond the current start of the art, and unless another thrustor, such as a water jet, becomes available for such a high-speed ship, it will be necessary to expend many testing and development dollars to improve the supercavitating propellor efficiency and increase the power-absorbing capacity of each propeller.

3.4.7 Transmission Development Requirements

Continued development of epicyclic, SEGMAG and superconducting-electric transmissions will be required if larger propulsion systems are to be utilized for high-speed ships. The electric transmission systems studied in Phase 1 of this report offer the promise of increasing ship design flexibility and accommodating power conversion system limitations. Therefore, it does seem reasonable that development programs should continue on at least one of the three electric transmission designs considered. Based on the limited information available, the SEGMAG concept appears to offer the most promise. However, mechanical transmission development must not be short-changed. Epicyclic transmissions could be attractive with continued reduction in specific weight and specific volume.

3.5 System Modifications For Demonstration Testing

It seems reasonable to assume that the lightweight ship propulsion system described in this report will not be installed onboard a ship until its design has achieved a substantial level of operational success. Demonstration testing prior to ship installation will require that certain modifications be made to the system in order to simulate the installed environment. For example, at the very least, a method for absorbing the output shaft power will have to be substituted for the propeller. If the demonstration test is to be performed on a full-size system many other modifications would be required. Yet, if the most cost-effective demonstration is sought, still other modifications such as reduced size or compromised performance might be prudent. These modifications will be discussed in the paragraphs which follow and are summarized in Table 3.7.

3.5.1 Full Scale Demonstration Testing Modifications

The demonstration of a full-size closed-cycle system, operated under a significant range of the expected critical operational conditions, would be desirable prior to installation in Navy ships. It is possible that such demonstrations could be performed without having undertaken subscale system demonstrations. In fact, this practice is commonly followed in the utility industry, particularly that in Europe. However, this approach calls for the fabrication of a one-of-a-kind demonstration unit which will typically be operated for a period of several years in order to identify problems and evaluate corrective changes. The advantage of such full-size demonstrations lies with the fact that once a system is made to operate satisfactorily, the manufacture of subsequent equipment can be undertaken with extremely high confidence in its operational success.

Two notable problems are associated with this full-size demonstration practice. Full-size demonstration testing is extremely costly, particularly if a significant design change must be made to solve a problem. Secondly, when dealing with large systems such as the CCGT propulsion system investigated in this program, it is often difficult to provide sufficiently large test equipment which will accurately simulate operational conditions. These high costs can often be reduced by using subscale testing, or by employing cost-saving short-cuts during testing. The modifications needed during full-scale testing will be discussed in the paragraphs which follow immediately, and the cost saving methods will be discussed later.

Initial demonstration testing of full-size systems will probably be performed on land rather than at sea. Therefore, power absorption equipment such as water brakes, or generator and resistor combinations, will have to be employed to simulate the propeller load characteristics. Power absorbing equipment of the size needed for this system is not readily available, and consequently, this uniqueness would be expected to cause testing and demonstration difficulties. It would also be expected that the variation of compressor

and turbine inlet pressures and temperatures will be restricted to a range smaller than that of actual operation conditions. The availability of cooling water, or heat exchangers to provide helium cooling, and potential heat exchanger compromises or equipment substitution, may also limit the capability of the demonstration test equipment. Furthermore, due to safety considerations, initial testing should not be expected to reach the level equivalent to that designed for the closed-cycle system. Limits to the amount of time and money available will minimize the amount of testing performed at maximum test pressures.

In addition to performance testing, a limited amount of endurance and shock testing should be scheduled. Duty-cycle modifications should be made to establish an endurance specification cycle which could accelerate the time needed to demonstrate the hardware reliability characteristics. Explosive shock testing will have to be performed on a mounting structure which simulates the support given to the propulsion system by the ship bedplate. After these tests are successfully completed, it may be possible to demonstrate further the propulsion system operation by installing the demonstration unit on-board a large existing ship.

A currently existing cruiser, battleship, or carrier might be used to provide at-sea testing of the initial demonstration propulsion system unit. Such ships, particularly those with four propellers, would allow the LWSPS-CCGT system to provide power to only one or two shafts. Such a ship would still be operational over a significant portion of its duty cycle without the requirement that the CCGT system be operated. Of course, in such an installation, the CCGT may be required to use the nonsupercavitating propeller designed for the selected ship, and therefore a modification in the overall gearbox reduction ratio may be necessary. This at-sea demonstration testing would be extremely valuable for evaluating this new propulsion system under a full spectrum of operating conditions and at the same time may be less costly than creating a special land-based test facility.

Many potential simplifying measures could be undertaken to reduce the complexity associated with full-scale demonstration testing. One such measure would be the use of a nonintercooled compressor configuration. This configuration would sacrifice efficiency and power output, but it would eliminate the need for an intercooler while requiring a redesign of the turbomachine high compressor. Other methods of simplifying and saving expense for the demonstration testing are discussed in subsequent sections of this report.

3.5.2 Subscale System Demonstration

Test and demonstration of a subscale, closed-cycle turbine propulsion system should allow considerable savings to be achieved when compared with the full-scale demonstrations just discussed. Subscale tests could be substituted for most, if not all, of the initial checkout tests and demonstrations of

performance and endurance characteristics. Full-scale tests would still be needed for the shock loading and at-sea demonstrations. The initial subscale testing could be performed at one of many existing Navy test facilities. Important work of this nature has already been performed on closed-cycle systems at the David W. Taylor Naval Ship Research and Development Center (Ref. 3.24).

Appropriate scaling of the turbomachinery, ducting, control valves, and heat exchangers could allow a majority of dynamic and transient operational characteristics to be examined and evaluated more economically. Any changes found necessary in the system design would then be much less costly, and tests of subsequent new designs could be undertaken in shorter periods with other subscale systems. Test facilities such as the Government-owned Tullahoma facility, the Trenton, New Jersey facility, or the Pratt & Whitney Aircraft Willgoos Laboratory might be used for this testing. As was noted with the full-scale testing, the compressor and turbine inlet temperatures and pressures may have to be restricted to a range smaller than the spectrum expected with actual ship operations. Possibly, even the at-sea tests could be performed with a subscale system. A subscale system might be installed on board a destroyer rather than a larger, more costly cruiser, battleship, or carrier-type ship needed for a full-size system demonstration.

3.5.3 Cost Saving Demonstrations

The basic closed-cycle gas turbine propulsion system could be demonstrated in a variety of configurations and arrangements in an effort to save significant amounts of testing and demonstration funds. The basic concept and operational characteristics could be identified, examined, and evaluated, by incorporating modifications discussed in the paragraphs which follow. In general, these modifications will result in a reduced power output, a decreased efficiency, an increased specific weight, or some other performance compromises.

A reduction in the maximum cycle temperature could probably provide the single largest saving in demonstration and testing cost. Reducing this temperature to approximately 700 C would allow the heater component to be constructed with much cheaper materials, yet the investigation of operational characteristics still could be carried out in a manner which would simulate the vast majority of operational requirements. Corrosion and endurance testing, however, would not be representative.

If regenerator effectiveness were reduced, significant savings could be made in the size and cost of the regenerator, and consequently in the cost of the system, since the regenerator represents a large portion of the CCGT system. The effectiveness would not have to be reduced very much in order to provide a significant savings in materials. This observation is based on an evaluation of regenerator effectiveness carried out in the Part I and Part II reports (Refs. 3.2 and 3.1). The cost of the regenerator might also be reduced

if commercially available larger diameter tubes were used. A larger tube size would mean a larger and heavier regenerator, but more conventional fabrication practices could be used, and the tubes might be cheaper since they are more readily available.

The heater components could also be modified to derive significant cost savings. Rather than use the configuration designed for this program, the heater could incorporate more conventional "boiler-type" heat transfer concepts. A large firebox, rather than individual pressurized combustors, might be used in the manner of some European power plants (Ref. 3.13). Furthermore, since the closed-cycle system might use many sources of energy, including nuclear, it would seem reasonable to first demonstrate the LWSP-CCGT concept with a large, heavy, conventional technology heater.

The equipment used for the first demonstration tests could also incorporate design compromises in several other areas. For example, a single-shaft gas turbine might simplify the design and fabrication of the turbomachinery. Such a design would have less flexibility for operational power variations, but could still be used to demonstrate the basic characteristics of a LWSP-CCGT system. Furthermore, a nonintercooled compressor design could be used for a demonstration, and although it would sacrifice performance in terms of reduced efficiency, it would eliminate some of the complexities of the inlet and outlet ports, ducting, heat exchangers, water circulating pumps and the associated equipment required for the intercooler.

The method which would demonstrate closed-cycle gas turbine systems most rapidly and cost effective is probably to use air as the working gas. Air turbomachinery characteristics are well known, and so are its heat exchanger characteristics. However, volume and weight would be sacrificed when using air as the demonstration medium. Furthermore, if the maximum pressure level were reduced from the design condition specified, existing air turbomachines could be used and thus would minimize the turbomachinery testing and development requirements. For example, a nonintercooled, air closed-cycle could use a portion of one of many large industrial gas turbine designs currently in production to provide power output near 40 MW. The basic attractiveness of closed-cycle systems would not be compromised when using the air as a working gas. Furthermore, the potentially desirable CCGT characteristics such as: the reduced corrosion of the turbomachinery due to absence of combustion products; the flexibility of fuel sources; the high efficiency at part load; and the control system characteristics; could still be evaluated with an air system.

3.6 Research and Development Schedules and Cost Estimates

If closed-cycle gas turbine propulsion systems are to be used in 1990 Naval ships, a large research and development (R&D) program must be started in the

near future. The time and cost requirements of this R&D program are estimated at almost ten full years and over $340 million, respectively. Even these requirements may be near the minimum levels needed to meet 1990 goals. In the sections which follow, first the schedule for the research and development programs are identified, and then the projected cost for these development items are summarized. The overall program schedule is presented in Fig. 3.5, while the annual and cumulative program expenditures are shown in Figs. 3.6 and 3.7.

3.6.1 Turbomachinery Research and Development Plans

The development of turbomachinery for use in a helium closed-cycle is expected to take almost ten years in a success oriented program. This effort is divided into three basic parts. First, the helium flow dynamics must be more completely understood beyond the state-of-the-art in current applications. This basic technology must then be incorporated into component development of the compressor and turbine sections. Next, the integration of all the necessary turbomachine components must be performed, and finally, a test program which demonstrates a full-scale, closed-cycle propulsion system must be completed prior to ship installation. Approximately $165 million would be spent over a ten-year period on the turbomachinery development described in the following sections.

3.6.1.1 Helium Flow Dynamics Research and Development Plan

Helium flow dynamics R&D must be performed to improve the state of the art in helium turbomachinery. Since the conceptual designs presented in this program will use components which are more heavily loaded than current helium or even some air machines, the characterization of individual blade shapes as well as the interaction of blades in a cascade must be identified in more detail. Boundary layer and end-wall conditions also must be better understood, and heat transfer characteristics within the flow path must also be evaluated. Consequently, basic flow tests as well as more complex tests, such as rotating stage rig tests and ducting pressure loss testing, will have to be conducted before a successful design can be expected.

Since some of the research and development requirements for these helium flow dynamic considerations have already been started (Ref. 3.14), the preliminary research and development program schedule presented in Fig. 3.5 shows dashed lines for activities prior to the beginning of 1981. However, if these current programs are not continued, it is believed that the earliest time at which a new program could be started would be the beginning of calendar year 1981; this fact is reflected on the research and development program schedule. The cost of the helium flow dynamics R&D, as shown in Table 3.7, is just under $10 million.

3.6.1.2 Turbomachinery Component Development R&D Programs

The most cost effective manner to develop a new turbomachine is to develop the major components separately and then integrate these components after the majority of design problem areas have been resolved and component performance has been proven. In the case of the large turbomachine for the CCGT propulsion system, the component R&D, particularly that for the low and high compressor, for the compressor drive turbine, and for the power turbine, should be performed on a sub-scale basis. In addition to reducing the cost of component fabrication, this approach will minimize the test facility requirements. However, for the sealing and bearing area components it is expected that full-scale testing will be most beneficial. This is due to the fact that the cost of fabricating these components can not be reduced significantly in a sub-scale system, and that the crucial problems associated with these components might develop only in a full-scale test.

Compressor development could be started no earlier than the beginning of calendar year 1982. At that time the detail design program can begin by using the early data from the helium flow dynamics R&D effort as a basis for turbomachinery specification. Some preliminary design effort might be initiated in 1981, but the value of this effort will depend on the amount of its interaction with the basic helium flow dynamics development.

As seen in Fig. 3.5, following the detail compressor design, fabrication of the sub-scale compressor components will carry the program through 1983. Testing to evaluate the performance of the entire low and high compressor sections will then be possible in 1984. Following the initial performance determinations, the more critical work on evaluating stall characteristics will continue the program through 1985.

During the late '84 and early '85 period it is expected that design revisions and fabrication of revised compressor designs will concurrently be started. The retesting of the sub-scale compressor components which include the revised designs can then be expected to occur during 1986. This overlapping of programs must be performed in order to prove out the entire closed-cycle system by the 1990 goal. The cost of the compressor R&D will be at least $30 million.

R&D for a compressor-drive turbine should commence in early 1982, first with the detail design and subsequently with the fabrication of the sub-scale turbine components. Cooling and secondary flow characteristics investigations could be performed in cold and hot rigs prior to the completion of all the compressor drive turbine hardware. It should be possible to evaluate these characteristics as well as the overall turbine performance starting in early 1984. Design revisions and fabrication of these revised designs, if necessary,

should be performed concurrently with the examination of the results from early testing so a revised design can be fabricated by the middle of 1985. Retesting could then prove out the performance of the revised design by early 1986 thereby allowing subsequent integrated tubomachinery development to proceed in a timely manner. As shown in Table 3.8 the cost of R&D for the compressor-drive turbine likely will exceed $20 million.

For the power turbine development, the planned program is very similar to the compressor-drive turbine development. Detail design and fabrication could begin in 1982 and extend through 1983; this would be followed by performance testing and separate rig testing of the exhaust section transition performance. Design revisions and refabrications, if necessary, must be started as soon as possible in 1984 and would carry into mid to late 1985. Retesting would then demonstrate the performance of the final design in 1986. The overall cost of power turbine development is projected to be slightly over $20 million as shown in Table 3.8.

Compartment sealing methods will be developed in full-scale rigs, rather than in sub-scale rigs for reasons explained earlier. Detailed design and fabrication of the compartment sealing areas could commence in 1981 and would carry through 1982. Testing in both rotating and stationary rigs could be expected to begin in 1983 and carry into mid 1984. Additional testing of the final design configuration could be expected to occur in 1985 or 1986.

Sealing methods for duct joints and valve stem areas should also be investigated and developed further. This testing and development should occur after the full system design has been established, and therefore will not begin until 1983 for the original design. When necessary, a second fabrication and test should be expected for a revised final design configuration. The testing of any auxiliaries needed to maintain pressure balance in regions such as the buffered seals prescribed in the Part-II report (Ref. 3.1) should also be evaluated for both the early and final design configurations. As shown in Table 3.8, the R&D on sealing methods should cost approximately $5.5 million.

Research and development into the appropriate bearing designs to be used in the CCGT system should begin as early as possible, since the final designs selected can have an important effect on determining the overall component layout. The conceptual design presented in the Part-II report (Fig. 3.5) uses journal bearings. However, other bearing concepts, such as gas bearings or anti-friction bearings, might also be applicable. Some work has already been performed in these areas under other ONR-sponsored programs (Ref. 3.14). Should these efforts continue, the results could be used prior to 1981 as an input to the CCGT R&D program decision making. In any event, beginning in 1981, a program should be instituted to evaluate the capabilities of these various bearing types and to select the desired bearing scheme before the end of 1981 such that detailed machinery designs can begin in 1982.

The detailed design and fabrication of the bearing compartment can be expected to be completed by the end of 1983. At that time, bearing rig testing could be undertaken to evaluate any potential problems in the selected design, and to identify limitations of these bearings and appropriate safety factors for the final turbomachinery design. Once the turbomachinery design has been finalized, a second set of bearing tests should be performed in the 1987-88 period to evaluate the performance of the final bearing configuration and arrangement. Overall, the bearing development program would cost approximately $4.5 million.

3.6.1.3 Integrated Turbomachine Development Programs

It is desirable to test and demonstrate a full-scale, closed-cycle gas turbine light-weight propulsion system subsequent to sub-scale testing but prior to installation on the selected ship type (such as a high-speed destroyer). This demonstration should follow a two-phase program. First, the turbomachine should be built and tested as an integrated unit, and then, the entire power conversion system (turbomachine, heater, heat-exchanger) should be demonstrated. The design and fabrication of the first full-scale demonstration prototype is expected to require almost four years. The final integrated design probably could not begin until the middle of 1984 after the component tests have evaluted early design components. The design of the full-scale system then should proceed concurrent with the redesign of the component hardware in order to facilitate fabrication of full-size hardware beginning in 1986. Initial checkouts of the full-size turbomachine and definition of its performance capabilities could begin in 1988. The important evaluation of transient response characteristics would carry the program well into 1989, and final endurance testing could be performed late in 1989 and early in 1990.

This entire test program is one which compresses a great deal of complex evaluations intc a short period of time. It should be expected to require a twenty-four hour a day operation for the entire development period in order to meet the goal of ship installation in 1990. In particular the transition from turbomachinery testing to total system demonstration will have to occur quickly and effectively to properly define performance, response and endurance.

A special test facility will be needed to perform this total system demonstration testing. The entire power conversion system will have to be assembled in a unified installation. Test capabilities will also be required to allow operation of the turbomachine without the heater; that is, testing must occur with another heat source, for a portion of the program. Preparation of this test facility will have to begin several years prior to the testing, with facility design beginning in 1984.

3.6.1.4 Turbomachinery Research and Development Program Cost

The development of the helium turbomachinery is expected to require a larger expenditure of funds than for development of any other CCGT system

component. Approximately $165 million will be required for the optimistic turbomachinery research and development program just identified. The majority of this money will be expended in component development, where at least $83.5 million will be spent. The full-scale integrated turbomachnery demonstration should require another $72 million, while the helium flow dynamics will add just under $10 million.

A detailed breakdown of the turbomachinery R&D costs is presented in Table 3.8. From this breakdown it can be seen that development of sub-scale flowpath components are the most costly operations of the development program. It should be appreciated that these costs include one complete design specification program as well as additional effort to modify the design for resolution of development problems. It should also be appreciated that this method of development will actually save money since the sub-scale development costs are less than the cost of one design and fabrication cycle for a full-scale turbomachine unit. Thus, significant savings are expected by using the sub-scale component development approach.

3.6.2 Control System Research and Development Program

The minimization of shipboard manpower requirements is expected to be a high priority with any future Navy propulsion system. Accordingly, to avoid a requirement for a high level of operational manpower in closed-cycle systems, computerized control technologies which are now, or will be available must be used. Because a closed-cycle helium system, like a steam system, presents a plethora of control factors which are all interrelated, the development of required control hardware will be a complex, costly, and time-consuming program.

In early 1981, the control requirements and strategy for operation of the closed-cycle system must initially be identified and incorporated into a preliminary control design. Extensive computer modeling of the system should then begin in 1982 using the expected characteristics of the system components. While this modeling is a very complex process, it can be expected to save many times its cost by reducing the number of hardware modifications ultimately required to provide stable system operation.

This extensive computer modeling effort could require as much as two years before an acceptable design evolves. Once this design is ready, a sub-scale system should be assembled and tested. To perform the sub-scale test, modifications will be required to both the control system design and to those sub-scale components which are available. Ducting, valving, and heat exchangers should be included in the sub-scale system test. The source of a sub-scale turbomachine will have to be investigated during the development program. For example, it may be derived from the sub-scale component development hardware or from an entirely separate turbomachine. If all developments proceeded normally,

testing of both the steady state and transient characteristics of the sub-scale system likely would be possible in the late 1985 to early 1986 period.

Some redesign effort will almost assuredly be required before the full-scale system components can be fabricated. However, this redesign and full-scale fabrication will have to be carefully integrated to allow full-scale propulsion system operation in late 1987 and subsequent delivery of the propulsion system in 1990. It is also probable that some new test facility equipment will be required for the sub-scale control system testing so time must be allowed for its appropriate design and fabrication. The total control R&D program will cost approximately $11.5 million.

3.6.3 Heat Exchanger and Heater Development Program

The research and development effort required for the heat exchangers and heater components, expected to be the second most costly portion of the CCGT R&D program, is estimated to cost $116.5 million. A complex program is planned starting with the compilation of material properties. The program would continue from subscale unfired testing through full-scale design, fabrication and testing. As can be seen in Fig. 3.5, the final component testing must be coordinated to integrate with the full-scale turbomachinery development so the overall system demonstration testing can commence prior to 1990. A more detailed breakdown of the program schedule and cost requirements is presented in Table 3.8 and discussed in the sections which follow.

3.6.3.1 Material Property Research and Development Program

Definition of material properties applicable to the CCGT propulsion system will rely both on current research programs and on new testing specifically tailored to the CCGT. However, the R&D programs specifically tailored to the CCGT system must be performed early in the development effort.

In particular, the corrosion resistance of the required alloys, when exposed to a spectrum of potential future fuels, must be identified. The results of such tests can strongly affect the design weight of the large CCGT heat exchangers since tube wall thicknesses are determined by the amount of material expected to be lost due to corrosion during the lifetime of the propulsion system. These corrosion tests should include examinations of ceramic materials, since the CCGT system could achieve large performance gains if a ceramic material were a viable alternative.

Of course, ceramic material testing, other than for corrosion resistance, must also continue in order to prove the acceptability of such properties as impact and thermal shock loading. This program must identify an acceptable ceramic material before the end of 1982 or it will not be possible to incorporate ceramics into the tight schedule for CCGT design and development.

The effects of long-term operation in a helium environment must also be understood more fully before either a metallic or ceramic material could be confidently used in a CCGT-LWSP system. Because it is difficult to predict analytically the effect of thermal transients on material performance, fatigue at weld joints or transitional regions, may have to be determined empirically. Due to the basic nature of the R&D material testing, these programs should be completed by 1983 and likely will incur expenses of slightly less than $9 million.

3.6.3.2 <u>Unfired Heat Exchanger Development Program</u>

The unfired heat exchangers, (the regenerator, precooler, and intercooler) required for the closed-cycle system are very large units, and the design requirements in terms of pressure loss and fabrication are severe. Therefore, it should be anticipated that considerable development will be required of these heat exchangers before the required design conditions can be met. Fortunately, this development can be confidently performed with subscale hardware. Either a basic module of each heat exchanger could be evaluated or an entire subscale heat exchanger unit could be fabricated. This development should follow the approach outlined in the paragraphs which follow.

The unfired heat exchanger development program could be initiated as early as 1981. The testing of the basic core design of subscale equipment would be undertaken simultaneously by testing promising inlet and outlet region flow paths. Establishing the losses in these inlet and outlet regions is a critical factor in meeting the overall system pressure loss design requirements, and testing of many revised designs should be expected during this progam which would continue into 1984.

Once the layout of the closed-cycle system is determined, the effect of valve and ducting geometry can also be evaluated. Such a program could start in 1982 and continue for at least two years during which time manufacturers' data for valve pressure losses would be combined with subscale model tests of the total system and other component data to establish pressure losses at these locations and others such as ducting joints. Testing of the closed-cycle heat exchanger and ducting system can be expected to continue into 1984 and recur in 1986 when the final design will be tested.

Test facility preparation would include work on equipment needed to mount and instrument the subscale models of the propulsion system, ducting, and heat exchangers. This effort should be fairly small and would be expected to be completed during 1982. As shown in Table 3.8 the total expenditure for unfired heat exchanger development should be approximately $17.5 million.

3.6.3.3 <u>Heat Exchanger Performance Evaluation Program</u>

The performance of the heat exchanger components, when subjected to design point temperatures and pressures, will be evaluated separately from the unfired

heat exchanger pressure loss evaluations just discussed. This performance will be evaluated in subscale testing where initially, basic rig testing should be expected to determine heat transfer characteristics in the helium environment. Following this basic testing, the fabrication of subscale components for testing under hot temperature conditions can be undertaken. Once these components are available for testing, the three basic heat exchanger components can be evaluated in separate tests of the regenerator, the precooler, and intercooler.

The schedule for the heat exchanger hot performance development is not expected to be time limited. More than a year of basic heat transfer testing is allowed prior to evaluating the actual designs. Testing the performance of separate modules of each heat exchanger is planned next, and this will continue into 1983. Following these tests, scale-model tests of each of the major components would commence and carry the program into 1985. Although the heat exchanger performance development program should cost approximately $9 million, it should not pace the ultimate evaluation of the entire closed-cycle system.

3.6.3.4 Full-Scale Heat Exchanger Development Program

Following the subscale heat exchanger testing, it will be necessary to verify the performance estimates through the fabrication and testing of full-size heat exchanger components. This program could start as early as 1985 and should be expected to continue into early 1987. Test facilities to perform these tests may be a major consideration for full-scale testing. Facility preparation, such as designing equipment to supply the appropriate helium flow conditions, must begin in early 1984 and be completed before the beginning of 1986. The overall cost of the full-scale heat exchanger fabrication and development will be nearly $30 million (see Table 3.8).

3.6.3.5 Full-Scale Fossil Heater Development Program

The development of the heater considered in this program could be the pacing item for the overall closed-cycle system development. This program is considered to be one of the most major items of development. As presented, this heater development program is a success-oriented program wherein no major redesign problems are anticipated. This program can be started in 1982 after the basic heat exchanger technology has been determined, and can be expected to last for almost five years at a total cost of almost $50 million.

Included in this full-scale heater development program are evaluations of transient performance capabilities, as well as of the structural effects on hot spots and thermal transients. Following the design of the heater system, fabrication of full-scale heater components could begin as early as mid-1983 with the expedited fabrication program being completed by mid-1985. Basic performance testing could begin near the end of 1985, with one of the earliest evaluations being performed on combustor operation. After combustor performance

is established for steady-state operation, part-load operation and potential design deficiencies can be investigated. In addition, the effect of hot spots which might develop in the heater system must be investigated if this heater is to be expected to endure for the desired lifetime of the system.

The effect of transient operations on the heater system must be tested extensively. The destructive effect of rapid thermal transients on large industrial heater and boiler structures is well documented, and in order to allow the LWSP design to meet the lifetime endurance requirements, the limitations on transient operation must be identified and design improvements must be made, within the testing schedule designated. Unfortunately, little time is available for these improvements in the compressed development program presented here. For example, in 1988, the heater testing is scheduled to be completed just as the integrated closed-cycle system is scheduled to commence testing. Thus, well-coordinated efforts are critical in achieving the goal of 1990 ship installation.

3.6.4 Other Propulsion System Component Development Program

The high-speed destroyer ship application identified in this program as being capable of utilizing the closed-cycle system, must also incorporate significant advances in technology in other power train components. Specifically, the supercavitating propeller, the thrust-bearing, and the epicyclic transmission must all be evaluated, tested and developed to states of the art beyond their current level.

3.6.4.1 Supercavitating Propeller Development Program

Many Navy programs have been directed toward improving the performance of supercavitating propellers. However, to implement such a propeller in the high-speed destroyer identified in this program, specific development efforts must be expected. In particular, the current efficiency of supercavitating propeller designs will probably have to be improved to attain the levels required for this application. This efficiency improvement program could be conducted with sub-scale testing, although since the size of the supercavitating propeller required for the high-speed destroyer (80,000 shaft horsepower) is well beyond that of any unit demonstrated today, expensive full-scale testing will also be required.

A sub-scale efficiency development program should be started as early as possible and will probably continue through three years of development. Development efforts intended to increase the output (power absorbtion) capacity should start in mid- to late-1983 and should require three more years of development. Expenses during the entire supercavitating propeller program are estimated at approximately $20 million.

3.6.4.2 Thrust Bearing Development Program

The naval architect firm which consultated on this program identified the thrust bearing as a potentially limiting technology (Ref. 3.21). They noted that the rather high speed (580 rpm) of the supercavitating propeller might preclude the use of existing thrust bearing designs from meeting the requirements of the high-speed destroyer. Therefore, full-scale design, fabrication, and testing of thrust bearing concepts should be conducted prior to shipboard operation of the CCGT propulsion system. While the thrust bearing program is not expected to be the pacing factor in the overall program, it would be sensible to evaluate this problem relatively early in the program, say in the beginning of 1983, so that a proven design would be available in 1985. An expense of about $6 million might be required to accomplish this goal.

3.6.4.3 Transmission System Improvement Programs

For the reference high-speed destroyer design, a mechanical gearbox has been selected as the transmission system. However, since the technology improvements needed to provide this gearbox are not considered extensive, it is felt that a development program should be performed which also examines the characteristics of both the improved epicyclic gearbox and SEGMAG or superconducting electrical transmissions.

Recent Maritime Administration (MARAD) programs have been directed toward developing epicyclic gearboxes with high capacity levels (Ref. 3.20). Perhaps such programs might be adapted to provide the transmission needed for the high-speed destroyer. At the same time, these programs should include efforts directed toward reducing the size requirements of these transmissions. The high-speed destroyer transmission design presented here uses gear tooth loading which exceeds the current MARAD program. Therefore, testing to evaluate these gear tooth loadings will be required before the goal transmission size can be attained.

If electric transmission developments proceed rapidly in the early 1980s, it is possible that these systems will look even more attractive than they have in the evaluations presented in this report. Therefore, it is recommended that the early years of the development program monitor the capabilities of SEGMAG and superconducting transmissions as they apply to the high-speed destroyer.

An estimate for the time and cost requirements for these transmission programs can not be all-inclusive. The relationship between on-going programs, new concepts, and the effort needed to develop an applicable technology are beyond the scope of this program. However, the transmission development program envisioned could be expected to last from 1981 through 1984 and cost about $17 million.

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TABLE 3.1

TYPICAL OPEN-CYCLE GAS TURBINE DESIGN PARAMETERS

Low Compressor	Current	1985-1990
Inlet Pressure Lose ($\Delta P/P$) %	0.7	0.7
Stage Efficiency (Polytropic) %	92	92
Corrected Air Flow Per Unit Area, lb/sec/ft^2	36-38	36-40
Corrected Tip Speed ($V_T/\sqrt{\theta}$) ft/sec	1100-1200	1200-1400
Hub/Tip Ratio, Inlet/Exit	0.50/0.80	0.50/0.80
Maximum Aspect Ratio (Mean Section)	3.0	3.0
Stage Pressure Ratio at 90-93% Efficiency	1.2	1.4
Flow Coefficient (Axial/Tangential Velocity)	0.5 → 0.7	0.5 → 0.7
Work Coefficient ($2_g J\Delta h/U^2$)	0.7 → 0.9	0.7 → 0.9
High Compressor		
Stage Efficiency (Polytropic) %	90	92
Corrected Air Flow Per Unit Area, lb/sec/ft^2	34 → 36	35 → 38
Maximum Corrected Tip Speed ($V_T\sqrt{\theta}$) ft/sec	1000	1400
Hub/Tip Ratio, Inlet/Exit	0.6/0.90	0.6/0.94
Minimum Aspect Ratio (Mean Section)	1.0	1.0
Flow Coefficient (Axial/Tangential Velocity)	0.5 → 0.7	0.5 → 0.7
Work Coefficient ($2_g J\Delta h/U^2$)	0.7 → 0.9	0.7 → 0.9
Combustor		
Combustion Efficiency %	100	100
Total Pressure Loss ($\Delta P/P$) %	4 → 6	3 → 5
Maximum Temperature Rise	1400	2300
Combustor Exit Temperature $^\circ$F	2100	2600
High Turbine		
Nominal Stage Efficiency (Polytropic) %	89	92
Typical Design Stage Work, Btu/lb	160	200
Maximum Hub/Tip Ratio	.88	0.91
Blade Height/Axial Width	1.0 → 2.5	1.0 → 2.5
Taper Ratio	0.8	0.65
Minimum Blade Mean Axial Width, in.	1.0	1.0
Minimum Vane Mean Axial Width, in.	1.5	1.5
Allowable Blade Metal Temperature, $^\circ$F	1550	1700
Velocity Ratio at Design	≥ 0.55	≥ 0.55
Vane Air Cooling Flow, % of Total Flow, Max	8 → 10	10 → 12
Blade Air Cooling Flow, % of Total Flow, Max	2 → 4	4 → 6
Low Turbine	**Current**	**1985-1990**
Nominal Polytropic Stage Efficiency	89	92
Maximum Last Stage Hub/Tip Ratio	0.75	0.75
Blade Height/Axial Width	2.0 → 6.8	2.0 → 6.8
Taper Ratio	0.8	0.65
Minimum Blade Mean Axial Width, in.	1.5	1.5
Minimum Vane Mean Axial Width, in.	1.5	1.5
Exit Diffuser Losses ($\Delta P/P$), %	1.5	1.5
Velocity Ratio at Design	≥ 0.55	≥ 0.55
Power Turbine		
Total Efficiency (Adiabatic), %	90	92
Last Stage Hub/Tip Ratio	0.5 → 0.6	0.5 → 0.6
Maximum Blade Length, in.	24	28
Minimum Blade Mean Axial Width, in.	1.5	1.5
Blade Mean Height/Axial Width	2.0 → 5.5	2.0 → 5.5
Taper Ratio	0.8	0.65
Velocity Ratio at Design	0.7 → 0.6	0.7 → 0.6
Maximum Allowable Blade Root Stress, psi	40,000	50,000
Exit Velocity, ft/sec	400 → 850	400 → 850
Exit Diffuser Losses ($\Delta P/P$) %	1.5	1.5

Table 3.2

Technological Barriers and Constraints of Closed-Cycle
Lightweight Ship Propulsion Systems

Turbomachinery Technology

Helium Flow Dynamics
Transient and Dynamic Operational Characteristics
Sealing and Bearing Designs
Critical Speeds
Ducting and Inlet/Outlet Pressure Loss

Heat Exchanger Technology

Cycle Temperature Limitations
Heater Operational Characteristics
Fabrication Techniques and Costs
Maintenance Practices

Overall System Technology

Control System
Electric Transmission Weight, Complexity, Cost
Supercavitating Propeller Performance and Capacity
Containment of Large Turbomachinery

Table 3.3

Removal of Turbomachinery Technological Barriers -

Barrier	Solution	Substitute
Helium Flow Dynamics	Extensive Testing of Stationary and Rotating Blade Shapes	Use air as working gas
Transient and Dynamic Operational Characteristics	Subscale Testing of Turbomachines for Stall and Transient Characteristics	Use existing air turbomachine with low power output
Pressure Loss	Subscale Rig Tests of Heat Exchanger, Inlet/Outlet and Duct Arrangements	Adjust performance after fabrication
Sealing and Bearings	Rig Tests of Sealing and Bearing Designs	Use existing air turbomachine
Critical Speeds	Extensive Design Study	Use proven design Use electric transmission or constant speed drive

Table 3.4

Removal of Heat Exchanger Technological Barriers

Barrier	Solution	Substitute
Cycle Temperature	. Rig Tests on 816 C Design	. Improved heat exchanger performance at the expense of fabrication cost
	. Corrosion Tests on Materials	. Addition of topping cycle
	. New Heat Transfer Concepts	. Change tube sizes, geometry
	. New Materials Testing (Ceramics, etc.)	. Reduce max cycle temp
Heater Operational Characteristics	. Monitor Oberhausen Developments	. Nuclear fueled heater
	. Subscale Testing	. Use proven boiler-type heater design
	. Computer Control Simulations	. Semimanual control
	. Corrosion Testing	. Use only clean fuels
	. Endurance Testing	. In-service evaluation
	. Combustor Part-Load Testing	. Limit duty cycle
Fabrication Costs	. Automated Heat Exchanger Assembly	. Accept higher volume and weight
Maintenance Practices	. New Procedures	. Accept increased weight and volume
	. Provision for Modular Removal	. Increased down-time

Table 3.5

Removal of Overall System Technological Barriers

Barrier	Solution	Substitute
Controls	. Extensive Computer Simulations	. Develop controls on first full scale test
	. Test Operation of Sub-scale System	. Restrict transient requirements
	. Monitor, Utilize, and Adapt Existing CCGT Methods	. Utilize electric transmission to simplify controls
Transmission Characteristics	. Continue Development of Epicyclic Transmissions	. Utilize offset mechanical transmissions
	. Develop SEGMAG or Superconducting Electric Systems Further	. Accept reduced payload/ volume, and increased complexity
Supercavitating Propellor Characteristics	. Continue Development and Testing	. Utilize water jet
		. Reduce ship speed 10 percent and use subcavitating prop.
		. Accept lower efficiency
		. Utilize more propellers per ship
Containment of Turbomachine	. Refine Modeling Methods	. Utilize proven designs at lower power
	. Test Failures Further	. More safety precautions
	. Add Heavy Shielding	
Thrust Bearing Load	. Detailed Design Study for 57 MW	. Multiple propellers
	. Develop Existing Capabilities	. Reduce thrust requirement

Table 3.6

Testing and Development Requirements

Turbomachinery Technology and Design Verification

- Blade Shapes
- Boundary Layer Characteristics
- Stall Characteristics
- Localized Heat Transfer Coefficients
- Operation of Turbomachine Components
- Integrated Turbomachine Operation

Heat Exchanger and Heater Technology and Design Verification

- Corrosion of Superalloys
- Helium Environment Effects on Material Properties
- Ceramic Corrosion Resistance
- Heat Exchanger Transient Thermal Stresses
- Operational Characteristics and Design Verification

Pressure Loss Characteristics

- Inlet/Outlet and Transition Losses
- Ducting and Valve Losses
- Heat Exchanger Losses

Control and Transient Operation Characteristics

- Interaction of Sub-Scale Model Components
- Turbomachine Transient Limitations
- Characteristics of Sub-Scale Heater
- Part-Load Limitations

Sealing and Bearings

- Full Size Rig Performance Characteristics

Supercavitating Propeller

- Continue Development
- Improve Efficiency
- Increase Output

Mechanical and Electric Transmissions

- Continue Testing and Development of Large Epicyclic Designs
- Continue Development of SEGMAG or Superconducting Designs
- Resolve AC/DC Tradeoffs

Table 3.7

System Modifications for Demonstration Testing

For Full-Scale As Designed System Demonstration

- Add Power Absorption System for Land-Based Demonstration
- Install for Power On One-Shaft of Existing Cruiser, Battleship, or Carrier
- Utilize Nonintercooled Cycle for Simplicity
- Set Compressor Inlet Temperature and/or Pressures to Convenient Level
- Simulation of Shock Testing

For Sub-Scale System Demonstration

- Demonstrate in Existing Land-Based Facility
- Install in Current Destroyer for Partial Power
- Simulate Heat Exchanger Effects in Tullahoma-Type Facility
- Set Compressor Inlet Pressures and/or Temperatures to Convenient Level

Cost-Saving Demonstrations

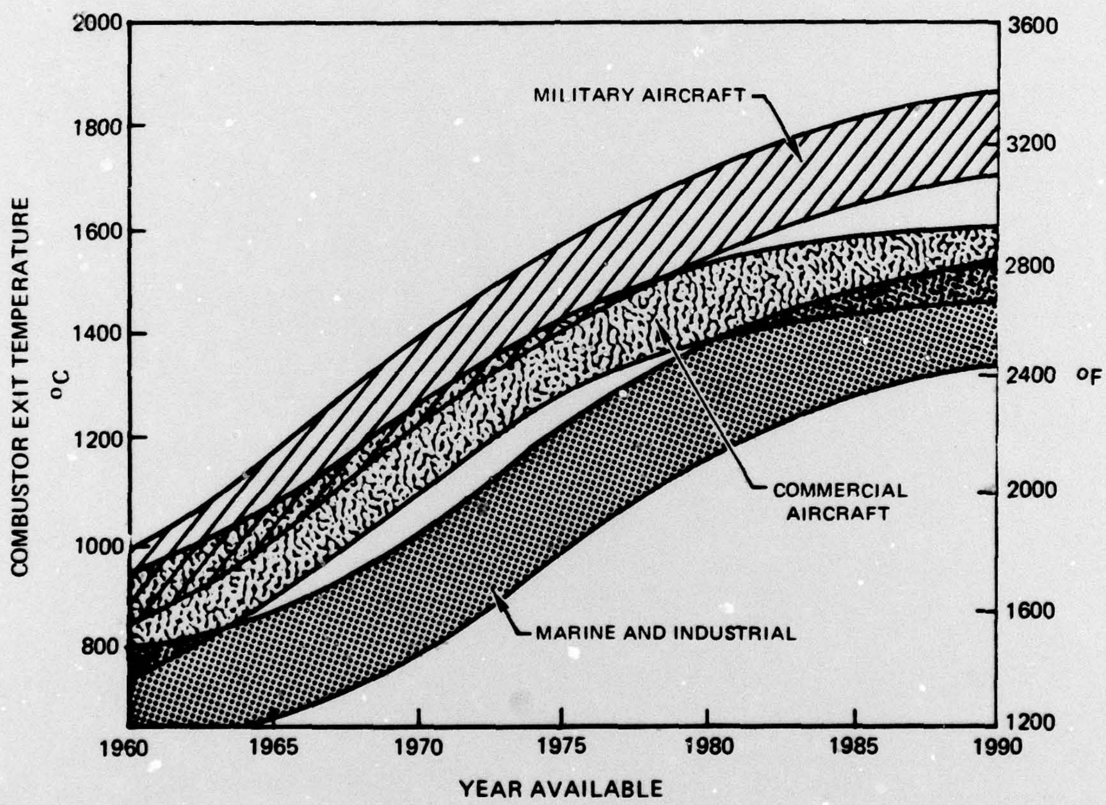
- Reduced Maximum Temperature Capability
- Reduced Regenerator Effectiveness
- Revised Regenerator Tube Size
- Modify Existing Boiler to Provide Heater Function
- Utilize Simpler Nonintercooled Cycle
- Utilize Revised Power Turbine Design (Single Shaft)
- Utilize Air for Working Gas (Reduced Output, Existing Turbomachinery)

Table 3.8

Cost Breakdown for Preliminary LSWP Research and Development Plan

	Millions of Dollars		
Turbomachinery			165.0
Helium Flow Dynamics (Subscale)		9.5	
Component Development		83.5	
Compressor (Subscale)	30.0		
Compressor-Turbine (Subscale)	22.5		
Power-Turbine (Subscale)	21.0		
Sealing Methods (Full Scale)	5.5		
Bearing Methods (Full Scale)	4.5		
Integrated Turbomachine Development (Full Scale)		72.0	
Design, Fabrication, Assembly	44.0		
Controls Checkout Test	2.0		
Steady State Performance Test	4.0		
Transient Response Test	4.0		
Endurance Test	6.0		
Test Facility Preparation	12.0		
Controls Development			11.5
Heat Exchanger and Heater Development			116.5
Material Properties		8.5	
Unfired Heat Exchanger Development (Subscale)		17.5	
Performance Evaluations (Subscale)		9.0	
Full Scale Heat Exchanger Development		27.0	
Full Scale Fossil Heater Development		49.0	
Operational Limitations		5.5	
Other Propulsion System Components			43.0
Supercavitating Propellor		20.0	
Thrust Bearing		6.0	
Transmission System		17.0	
Management			7.0
Total			343

COMBUSTOR EXIT TEMPERATURE PROGRESSION IN OPEN–CYCLE GAS TURBINES



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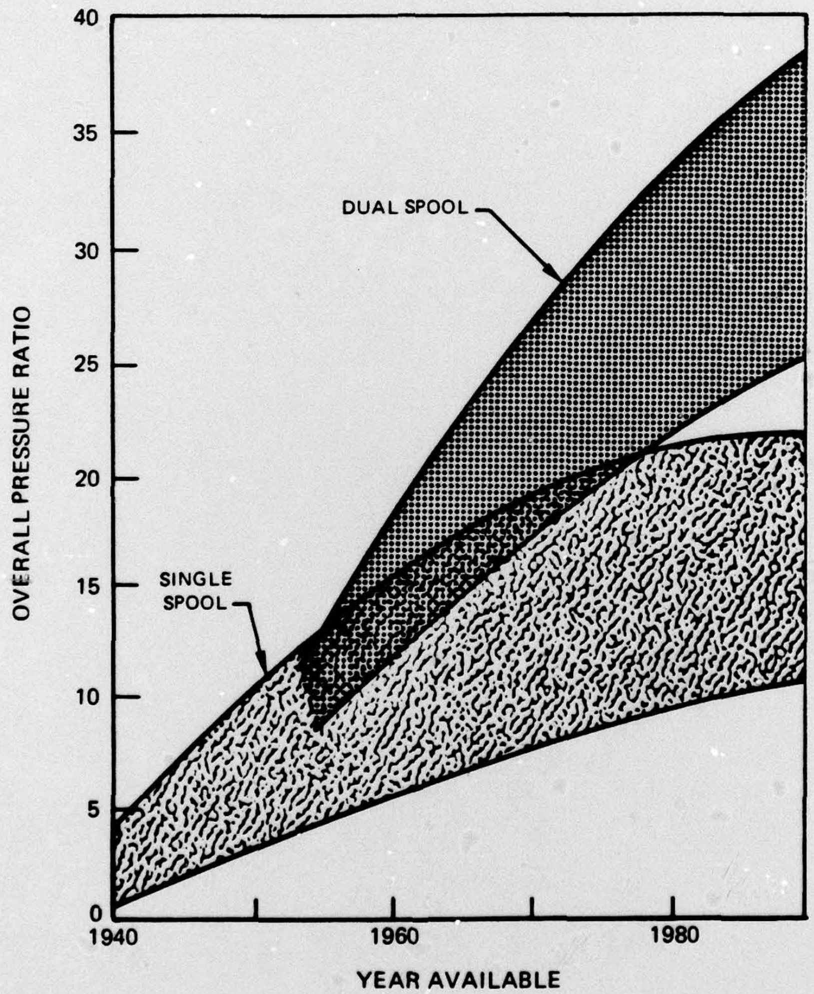
PROGRESSION OF OPEN–CYCLE GAS TURBINE PRESSURE RATIO



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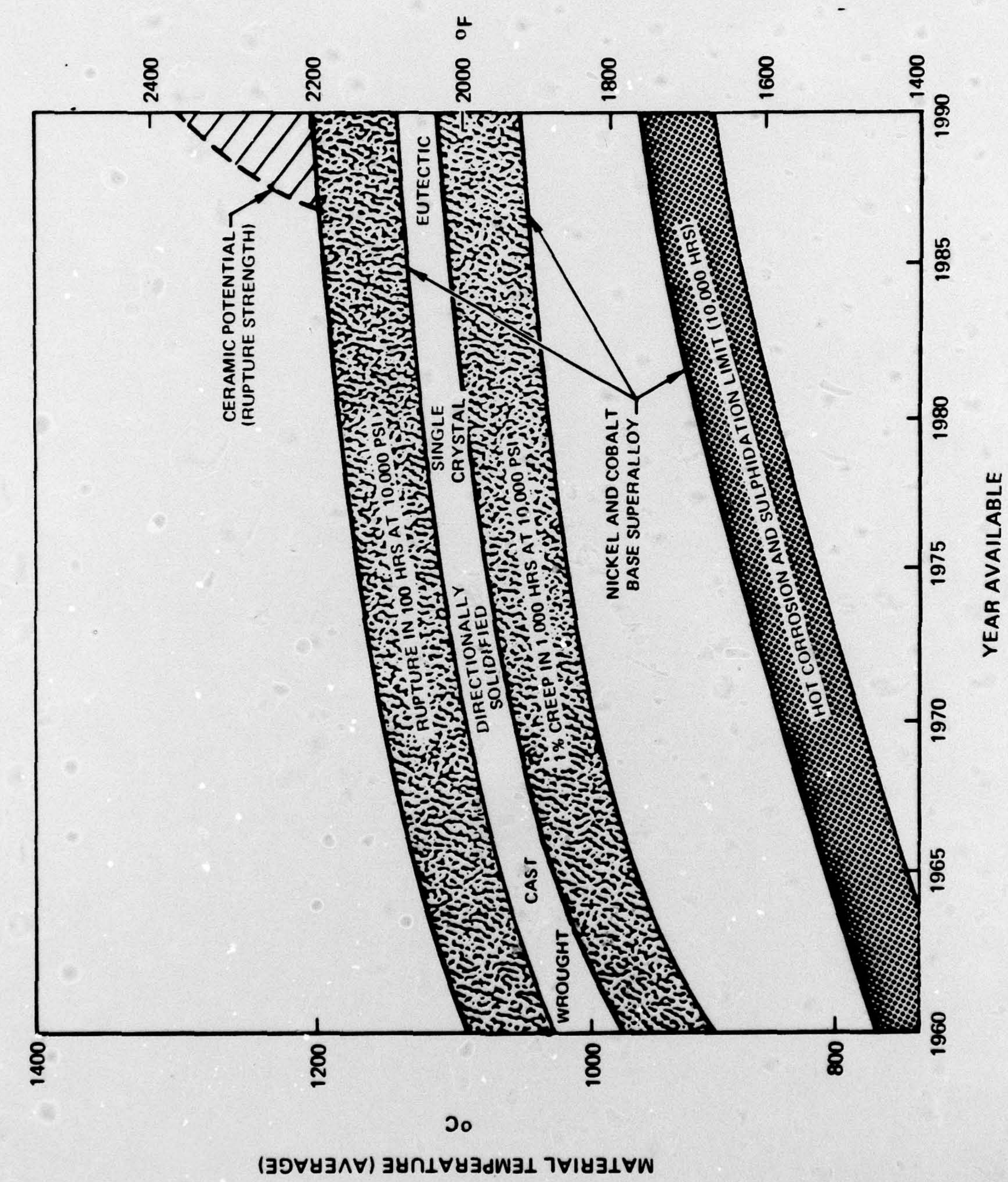
ADVANCES IN HOT SECTION MATERIAL PROPERTIES



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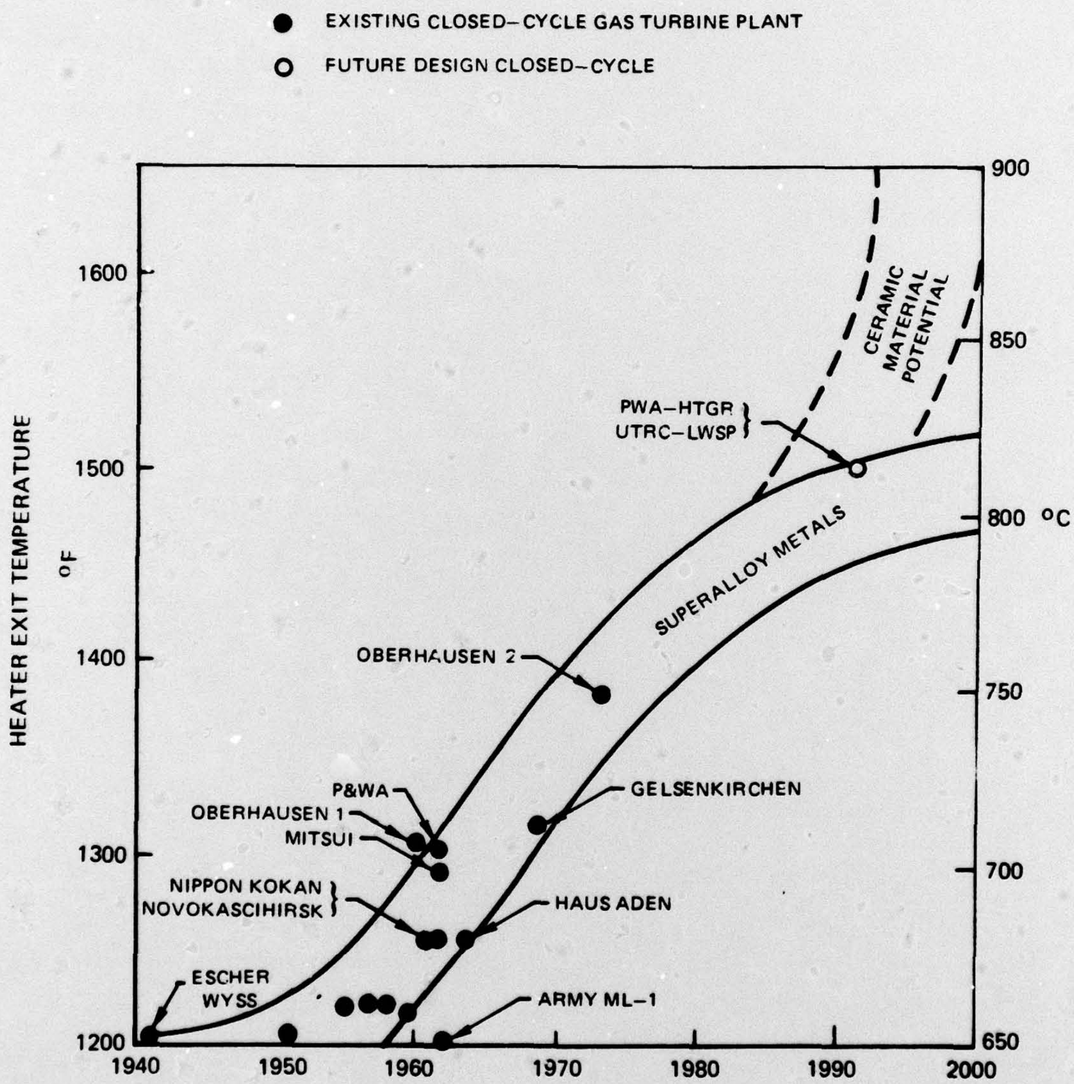
PROJECTED CLOSED–CYCLE GAS TURBINE MAXIMUM TEMPERATURE PROGRESSION



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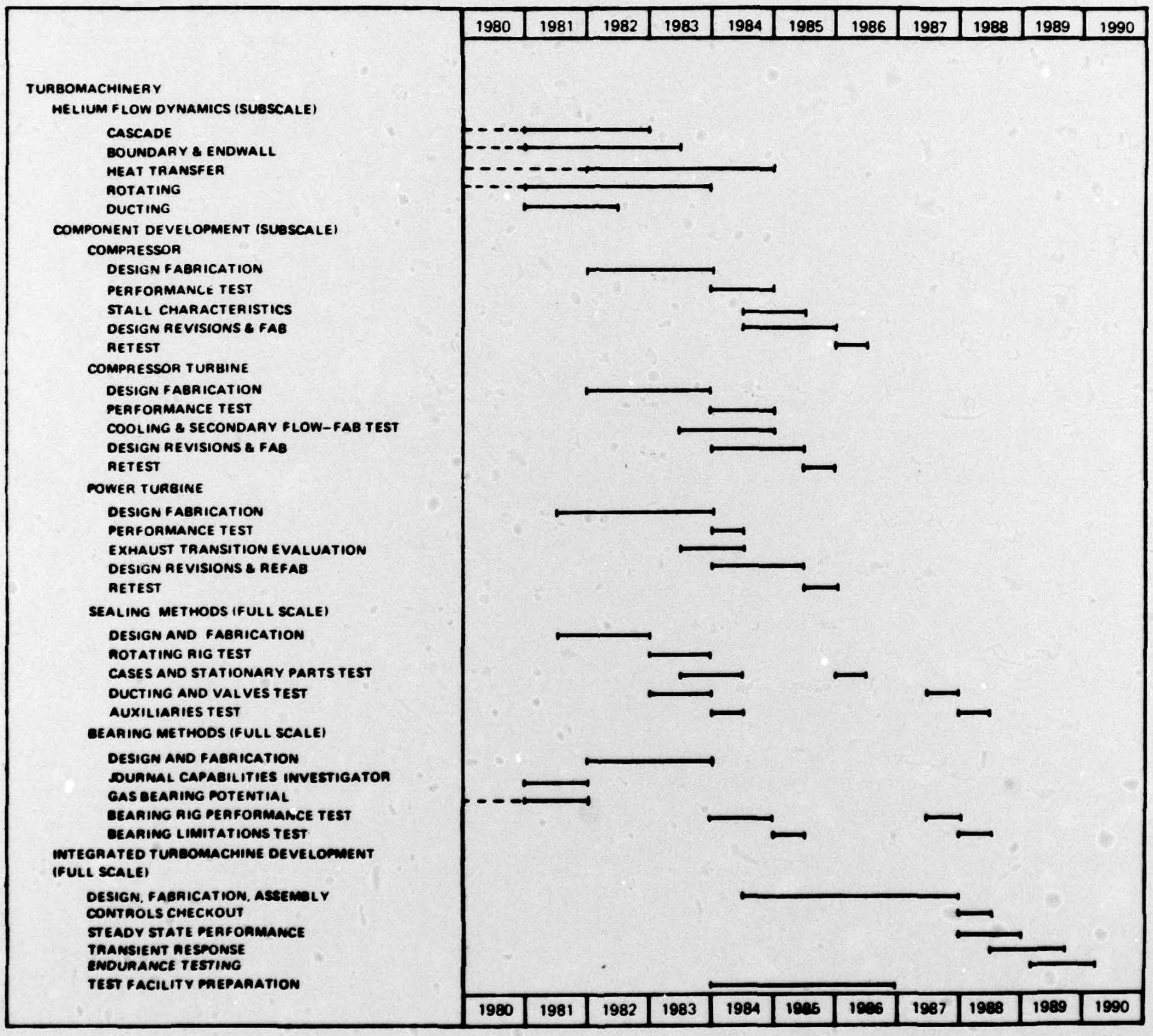
PRELIMINARY RESEARCH AND DEVELOPMENT PROGRAM SCHEDULE



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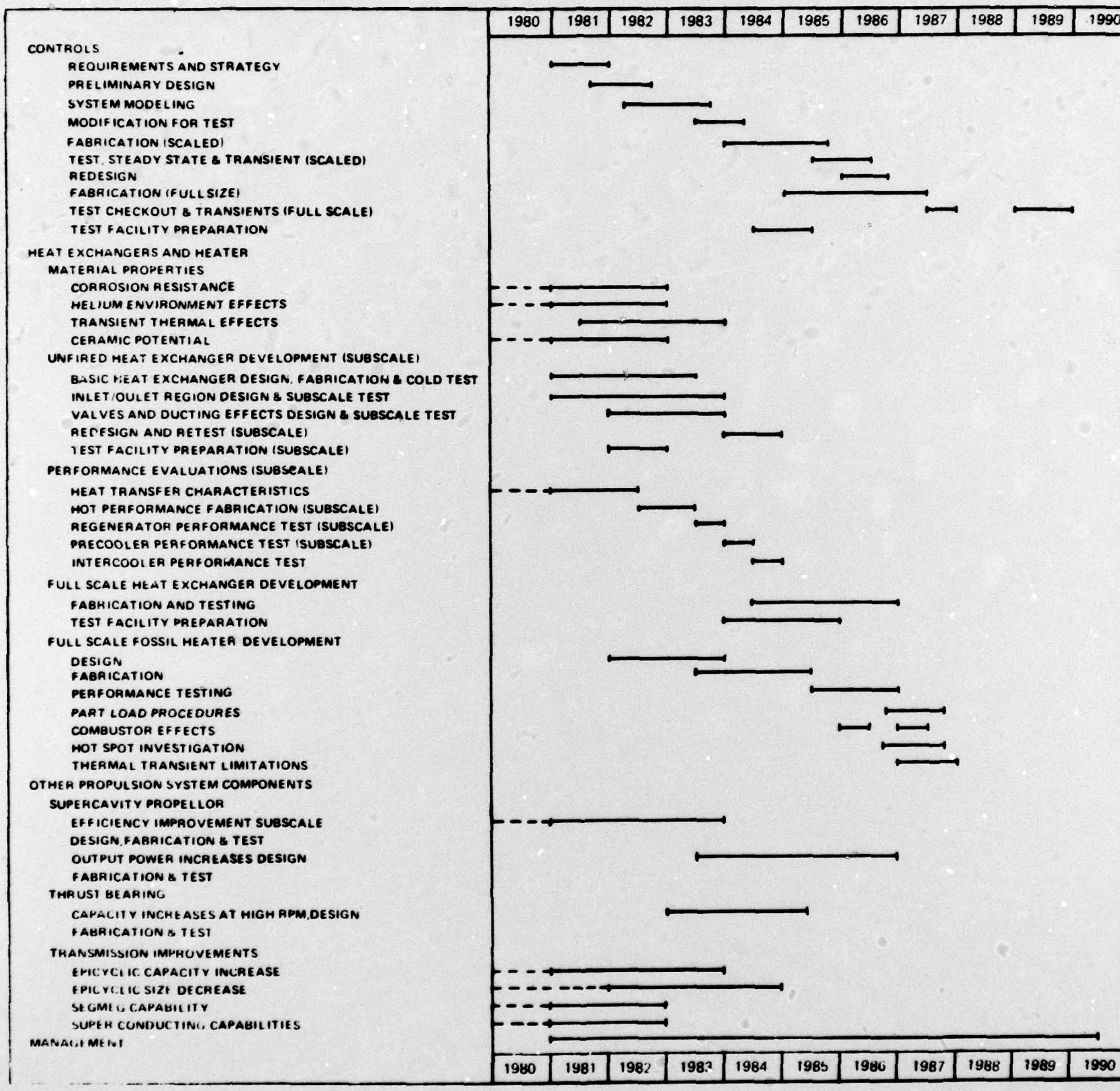
PRELIMINARY RESEARCH AND DEVELOPMENT PROGRAM SCHEDULE (CONT'D)



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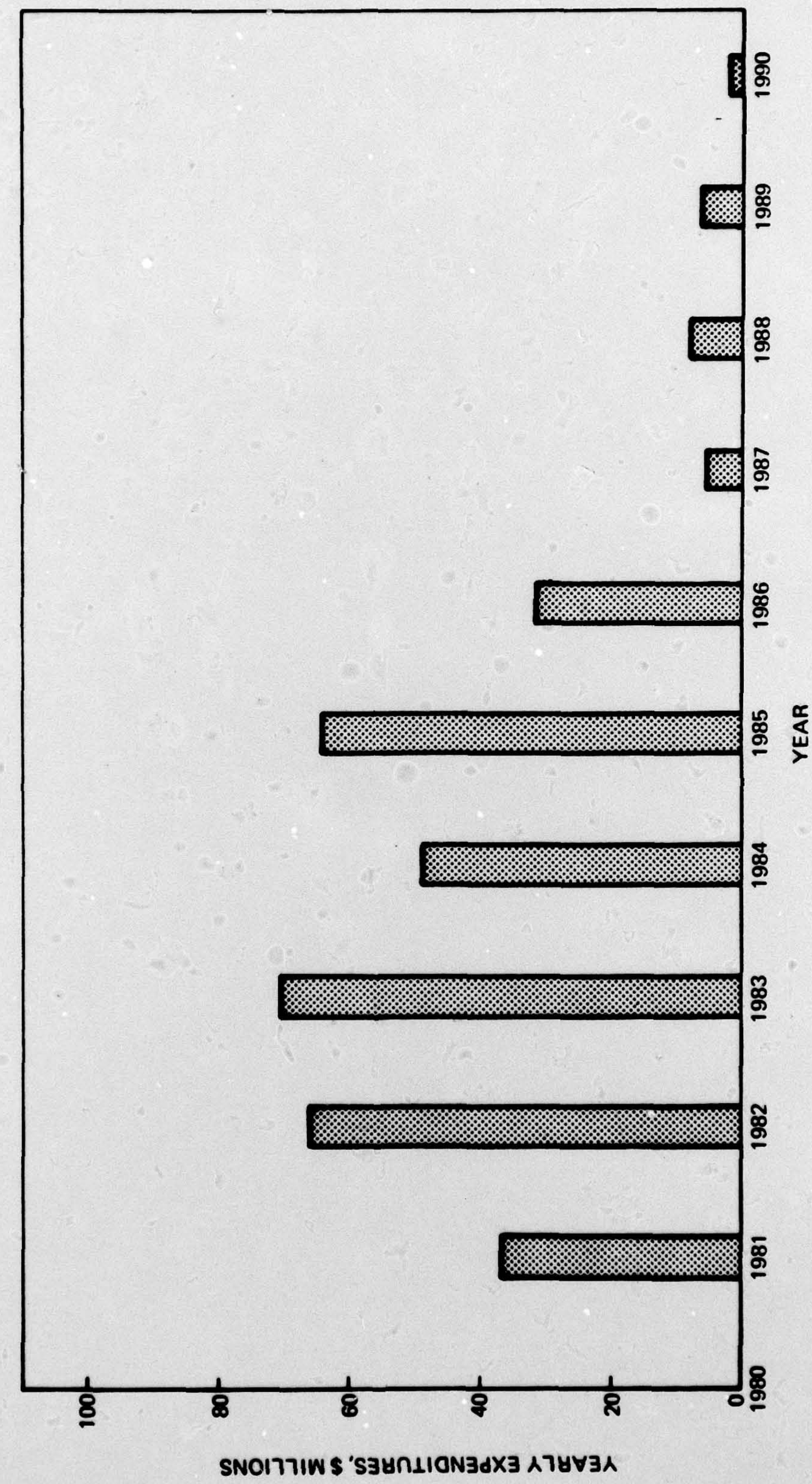
ESTIMATED YEARLY CCGT–LWSP RESEARCH AND DEVELOPMENT PROGRAM EXPENDITURES

- GOAL OF 1990 SHIP INSTALLATION
- SUCESS ORIENTED PROGRAM



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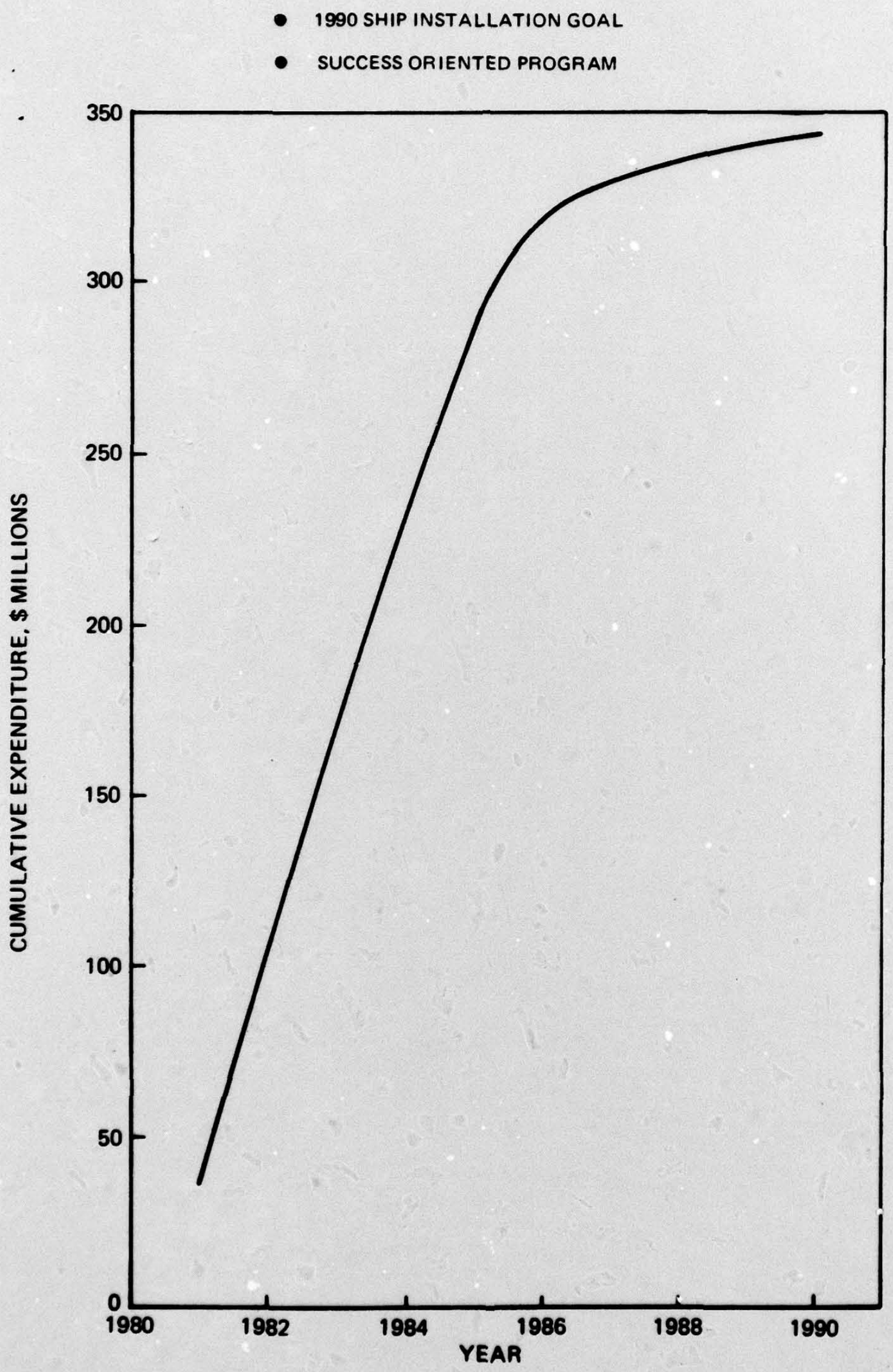
ESTIMATED CUMMULATIVE COST FOR DEVELOPMENT OF CCGT–LWSP SYSTEM



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